BLENDING OF ETHANOL IN GASOLINE FOR SPARK IGNITION ENGINES

PROBLEM INVENTORY

and

EVAPORATIVE MEASUREMENTS

AVL

M T C

REGISTRERINGSUPPGIFT

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Sammanfattning:
Presently all gasoline sold in Sweden contain 5 % of ethanol. Ethanol mixing above 5% is not possible because of the EU-fuel directive as well as The European standard EN 228. However, there is in Sweden an interest in further increasing the bio-ethanol content in gasoline up to at least 10 %. The main reason is that even relatively small percentage additions will result in a substantial total volume of gasoline substitution, and the present infrastructure for distributing fuels can be used largely unchanged.
Based on that background the purposes of the study were to collect information on national and international findings and experience related to the use of blends of ethanol in gasoline as fuels in spark ignition engines. The project also included a first study on the impact of the evaporative emissions with different grades of base gasoline and different blending proportions of ethanol.
The main conclusion from using ethanol-gasoline blends in practice is that blends with up to 15 percent ethanol will not have any significant negative effects on the wear of the engine or vehicle performance.
No significant difference can be seen in regulated emissions when comparing the use of blended fuel (with up to 10-15% ethanol) to the use of neat gasoline. Concerning unregulated emissions views differ. Regarding the emissions of benzene, toluene, ethyl benzene and xylene (BTEX) the main conclusion is that there is a slight decrease when using ethanol blends, while for aldehydes there is a significant increase, especially of acetaldehyde and (to a lesser extent) formaldehyde emissions. However, there is a serious lack of data describing the effects under Swedish conditions.
There will be a slight increase (~2-3%) in fuel consumption when shifting from neat gasoline to a 10 percent ethanol-gasoline blend, depending on the design of the vehicle. Cold starts, in particular, will affect fuel consumption more when using blended gasoline than when using neat gasoline.
There is a need to generate data and experience by running tests and analysing the environmental effects of blending ethanol with gasoline. The lack of data is more marked for blends with high ethanol contents (~20 %). Such blends should be avoided before a thorough analysis has been carried out and more data are available.

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Engelska: Ethanol, Blending, Gasoline, Exhaust emissions, Regulated, Unregulated, LCA, Alcohol fuels, Alternative fuels, Evaporative emissions, Vapour pressure, RVP,
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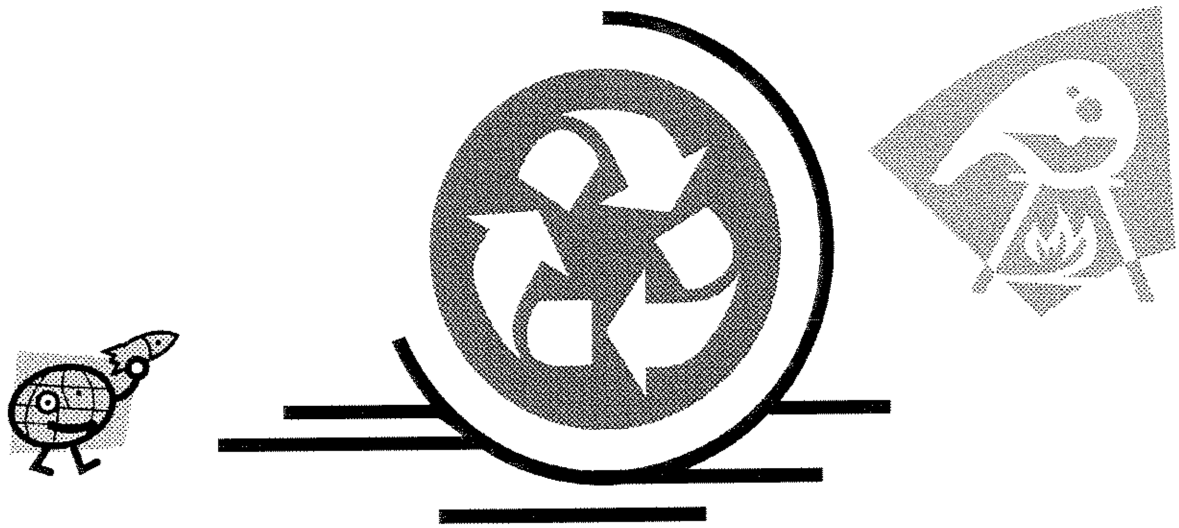

BLENDING OF ETHANOL IN GASOLINE FOR SPARK IGNITION ENGINES

PROBLEM INVENTORY

and

EVAPORATIVE MEASUREMENTS

Study performed by Stockholm University, ATRAX AB, Autoemission KEE Consultant AB, AVL MTC AB.

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Contents

0. SUMMARY

The purpose of the study reported here was to collect information on national and international findings and experience related to the use of blends of ethanol in gasoline as fuels in spark ignition engines. The main reason for blending ethanol with gasoline is to reduce fossil carbon dioxide emissions (and thus the greenhouse effect) from vehicles by using bio-ethanol originating from renewable sources. Presently all gasoline sold in Sweden contain 5 % of ethanol (here and throughout the text such percentages refer to the alcohol content of blends by volume) and the relevant authorities are interested in further increasing the bio-ethanol content in gasoline. Blending bio fuels with a petroleum-based fuel has the twin advantages that even relatively small percentage additions will result in a substantial total volume of gasoline substitution, and the present infrastructure for distributing fuels can be used largely unchanged.

Another aim of the project was to study the impact of using such blends on evaporative emissions by carrying out measurements with different grades of base gasoline and different blending proportions of ethanol. A report on these measurements can be found in the appendix to this report.

The results and experience presented in this report originate from Sweden, the USA, Japan, Brazil, China, India, Thailand and Australia. The main topics discussed are the effects of using blends on: vehicle performance, cold starts and drivability, fuel and lubricating oil performance, service and maintenance, compatibility and wear, vapour lock, emissions (regulated and unregulated), fuel consumption, fuel energy content, Reid Vapour Pressure (RVP) and Life Cycle Analyses. The main conclusions of the study are as follows:

- There is intense interest world-wide in using ethanol as an automotive fuel, especially in blending ethanol with gasoline. Blending ethanol in a commonly used fossil fuel is generally seen as an easy way to introduce an alternative such as bio-ethanol without costly changes of the fleet of vehicles on the road.
- Ethanol can easily be blended in gasoline by well known methods. Ethanol has a lower heating value than gasoline, which will reduce the energy content of the fuel. However this can be partly offset by the higher octane value of ethanol.
- The main conclusion from using ethanol-gasoline blends in practice is that blends with up to 15 percent ethanol will not have any significant negative effects on the wear of the engine or vehicle performance.
- No significant difference can be seen in regulated emissions when comparing the use of blended fuel (with up to 10-15% ethanol) to the use of neat gasoline. Concerning unregulated emissions views differ. Regarding the emissions of benzene, toluene, ethyl benzene and xylene (BTEX) the main conclusion is that there is a slight decrease when using ethanol blends, while for aldehydes there is a significant increase, especially of acetaldehyde and (to a lesser extent) formaldehyde emissions. However, there is a serious lack of data describing the effects under Swedish conditions.
- There will be a slight increase (~2-3%) in fuel consumption when shifting from neat gasoline to a 10 percent ethanol-gasoline blend, depending on the design of the vehicle. Cold starts, in particular, will affect fuel consumption more when using blended gasoline than when using neat gasoline.

There is a need to generate data and experience by running tests and analysing the environmental effects of blending ethanol with gasoline. The lack of data is even more marked for blends with high ethanol contents (~20 %). Such blends should be avoided before a thorough analysis has been carried out and more data are available.

In the light of the situation and conditions in Sweden and the other countries belonging to the European Union there are certain barriers to overcome in order to succeed with the intention to increase the content of ethanol in blended gasoline. In addition, given the differences in conditions and regulations between Sweden, other countries belonging to the European Union, and regions where there is long experience of running vehicles on blended fuels, a number of issues have to be addressed before the alcohol content of blends is increased.

A first issue to address is the problem that the RVP increases when ethanol is blended with gasoline since current gasoline standards impose limits on its RVP. Therefore, either there must be an exemption for ethanol blended fuels or the base gasoline RVP must be adjusted. Such adjustments are already made today to the base gasoline used in the 5 % ethanol gasoline blends.

A second issue is concern about the performance and start-ability of vehicles at low temperatures, which commonly occur in wintertime, especially in the northern parts of Sweden.

A third issue is whether blends with 10 to 15 percent ethanol in gasoline will affect human health and the environment (both local and regional).

The report includes 181 references and was financed by the Swedish Emission Research Program (Emissionsforskningsprogrammet, EMFO).

1. INTRODUCTION

1.1. Background

A challenge that humanity must take seriously is to limit and decrease the greenhouse effect caused by various human activities.

A major contributor to the greenhouse effect is the transport sector* due to the heavy, and increasing, traffic levels. In spite of ongoing activity to promote efficiency, the sector is still generating significant increases in CO_2 emissions. As transport levels are expected to rise substantially, especially in developing countries, fairly drastic political decisions may have to be taken to address this problem in the future. Furthermore, the dwindling supply of petroleum fuels will sooner or later become a limiting factor.

An important step in efforts to solve the problem is to replace fossil source energy with bioenergy. In the transport sector this means either introducing bio fuels and using adapted vehicles, or blending bio fuels with petroleum-based fuels for use with present vehicle fleets. The two alternatives are not, of course, mutually exclusive. However, blending bio fuels with petroleum-based fuels for use by the present conventional vehicle fleets has the advantages that even using quite low blending concentrations will result in substantial total volumes of gasoline being substituted by bio fuels, and that the present infrastructure for distributing fuels can be used.

Today, the transport sector is a major contributor to net emissions of greenhouse gases, of which carbon dioxide is particularly important. In Sweden this sector accounts for roughly 20 % of total energy consumption, and almost 50 % of the total net emissions of carbon dioxide. The carbon dioxide emissions originate mainly from the use of fossil fuels, mostly gasoline and diesel oil in road transportation systems, although some originates from other types of fossil fuels such as natural gas and Liquefied Petroleum Gas (LPG).

If international and national goals (such as those set out in the Kyoto protocol) for reducing net emissions of carbon dioxide are to be met, the use of fossil fuels in the transport sector has to be substantially reduced. This can be done, to some extent, by increasing the energy efficiency of engines and vehicles and thus reducing fuel consumption on a volume per unit distance travelled basis. However, since the total transportation work load is steadily increasing such measures will not be sufficient if we really want to reduce the emissions of carbon dioxide. In order to reduce absolute amounts of these emissions we have to go further and an additional measure that will be required is to replace fossil vehicle fuels with renewable ones. Primarily, especially in the short term, this means bio-based fuels.

Probably the best candidate bio fuels to replace gasoline in the short term are alcohols. Alcohols can be blended with gasoline or used as neat fuel in both optimised spark ignition engines and compression ignition engines. In the medium term ethanol produced from grain will probably be

* Approx 30% according to the Annual Report of Greenhouse Gas Emissions from the Swedish EPA. 2002

the most important alternative fuel for replacing gasoline, and in the long term ethanol produced from cellulose might take over from grain ethanol.

Today, ethanol accounts for a substantial part of the alternative fuel market, especially in Brazil, the USA and Sweden. The advantages of ethanol are that it can:

- Provide a viable alternative to reduce the greenhouse effect.
- Be produced domestically, thereby reducing dependence on imported petroleum.
- Be easily mixed with gasoline.
- Be used (and already is on a wide scale) as an oxygenate in gasoline.
- Create new jobs in the country related to its production.[3]

From an international perspective, most research up to 1990 was focused on blends of methanol and gasoline, but some studies were carried out on ethanol-gasoline blends. Since these studies were carried out in the USA, it can be assumed that they mainly included vehicles with efficient emission control systems, but at the same time technical features of cars in the USA have historically differed, at least in part, from those in Sweden. It should also be noted that for a long time 10% ethanol has been added to commercial gasoline in many parts of the USA. In the USA there is considerable experience of adding higher proportions of ethanol to gasoline than those allowed by gasoline regulations in Sweden (Europe). The primary advantage of adding a bio-based alcohol to gasoline is that it reduces net CO_2 emissions but it also has other positive effects, such as increasing the octane value of the fuel and reducing the benzene content of the exhaust gases.

The use of alcohol blended gasoline and neat fuel alcohols as substitutes for neat gasoline have become matters of interest in many countries. The International Energy Agency (IEA), established in 1974, follows the development, and data and other experience from various trials have been presented and discussed at symposia organised by the International Symposium on Alcohol Fuels (ISAF). The first ISAF-symposium was organized in Stockholm 1978 and since then a symposium has been organized every 2 to 4 years.

Today, almost all the alcohol fuel used is ethanol and it has three main uses in Sweden: as neat ethanol in ca 400 buses; in a gasoline blend (E85) for Flexible Fuelled Vehicles (FFVs), of which approximately 17 000 were being used in Sweden in February 2005; and as a component of all of the other gasoline (E5) used throughout the country. This means that the most common alternative fuel used in Sweden is ethanol. Only approximately 65 000 m^3 (50 000 m^3 from wheat and 15 000 from cellulose) of this alcohol is domestically produced and at the time of writing around 165 000 m^3 is imported from Brazil. The goal for the future is to increase the amount of domestically-produced ethanol from cellulose (ligno-cellulose) and one step toward this goal is research to be carried out at a pilot plant.

The goals of the project presented in this report are to accumulate the data required to facilitate increased use of bio fuel by:

- Studying available literature, collected knowledge, identified data as well as yet undocumented experience concerning emissions when using ethanol blended gasoline.
- Evaluating the relevance of existing investigations and the data generated in them.
- Assessing what (if any) emission studies are needed to estimate reliably the effects of using ethanol blended gasoline on total emissions, both qualitative and quantitative.
- Measuring evaporative emissions from the combustion of different blends of ethanol and neat gasoline.

1.2. Alcohol Blended Fuels

The idea of adding low contents of ethanol or methanol to gasoline is not new, extending back at least to the 1970s, when oil supplies were reduced and a search for alternative energy carriers began in order to replace gasoline and diesel fuel. Initially, methanol was considered the most attractive alcohol to be added to gasoline. Since methanol can be produced from natural gas at no great cost, and is quite easy to blend with gasoline, this alcohol was seen as an attractive additive. However, when using methanol in practice it became clear that precautions had to be taken when handling it and that methanol is aggressive to some materials, such as plastic components and even metals in the fuel system. A lesson learned was that new, more resistant materials had to be used in the fuel system of the vehicles as well as in the distribution system. These experiences were also of great value when ethanol came to be more commonly used as an alternative to the commercial fuels, since even ethanol can be characterized as an aggressive fluid, albeit somewhat less so than methanol. The interest in producing an alternative fuel based on biomass has also been a major factor in the early choice between methanol and ethanol.

The use of E85, a mixture of 85 % ethanol and 15 % gasoline, for FFVs has become common. Blends with other percentages of ethanol in gasoline are commonly used in various countries around the world, especially Australia (officially 10 %), Brazil (up to 25 %), Canada (10 %), Sweden (5 %) and the USA (up to 10 %). There is still debate about whether, how and to what extent ethanol in gasoline may affect the materials in the vehicle and cause excessive wear of parts in the fuel system and the engine. However, in the USA, car manufacturers have agreed that use of gasoline with up to 10 % ethanol will not affect the warranties of their vehicles (Science Fair Projects Encyclopaedia, 2004; Launder, 2001). In his MSc thesis Launder described the development of the use of fuel alcohol, especially the use of ethanol in the USA. Amongst other salient facts noted by Launder "Minnesota has also passed legislation requiring the use of 10% ethanol in all gasoline".

Since both methanol and ethanol have considerably lower energy contents (15.7 MJ/l and 21.4 MJ/l, respectively) compared with gasoline (approximately 35 MJ/l) use of an alcohol-containing blend may affect the power output of the engine to varying degrees, depending on its design. In section 6 the calculated effects on the energy content of the fuel of blending ethanol with a specific gasoline are presented. According to these calculations, adding ethanol to a final volume of 10 % to a gasoline with an energy content of 32.3 MJ/litre will decrease that value by 3.4 %.

Blending alcohol in gasoline will affect, inter alia, the vapour pressure of the fuel and, as shown in section 8, the increase in vapour pressure is considerably larger when blending methanol than when blending ethanol. The alcohol is commonly added to gasoline when filling the tank of the vehicle that will deliver the fuel to the gas stations. More sophisticated blending technologies such as Ratio Blending, Sidestream Blending and Wildstream Blending are described and discussed in a paper by Toptech (2004). Of these "Ratio Blending" is designed for use when up to six components are to be blended. "Sequential Blending" of ethanol in gasoline means that the two components are pumped to the delivery truck in sequence. Even if it is computer controlled there are some uncertainties about whether the resulting mixtures will fulfil their specifications. "Sidestream Blending" is similar to ratio blending and is used when two or more components are to be mixed together and "Wildstream Blending" can be used when blending ethanol with gasolines of many different qualities simultaneously. In Figure 1.1 the configuration of Sidestream Blending is shown.

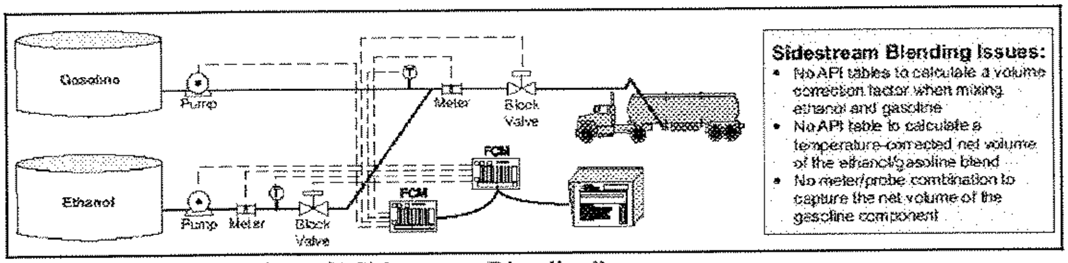

Figure 1.1. Configuration of "Sidestream Blending"

Since there are concerns related to the fact that ethanol is readily miscible with water it is important to use water-free systems when blending ethanol in gasoline. It is, of course, also important to use cost-efficient methods.

At least five major reasons for blending ethanol in gasoline are discussed, including the following advantages of using ethanol as an alternative fuel:

1. Reduction of net carbon dioxide emissions, to mitigate global warming.

2. The need to replace petroleum fuels with a renewable fuel

3. The need (especially in the US) to improve the air quality in non-attainment areas, i.e. areas of the country where air pollution levels persistently exceed the national ambient air quality standards.

4. The need to reduce the dependence on imported fuels.

5. To create new jobs in the country by national production of ethanol.

In Table 1.1 selected fuel properties for a neat gasoline and ethanol blends with the neat gasoline are shown. Density, RON and MON numbers and the IBP (initial boiling point) of the blended fuels increase as ethanol contents increase, while 10 %, 90 % and FBP (final boiling point) decrease. Using the blended fuels reduces brake specific energy consumption.

Table 1.1, Fuel properties of ethanol gasoline fuel blends (He et al., 2003)

Fuel parameters	Neat gasoline	E10 (10 % ethanol)	E30 (30 % ethanol)
Density at 19°C	0.736	0.741	0.751
RON	92.4	95.0	99.7
MON	81.2	82.3	86.6
IBP	36.0	37.5	40.0
10%	55.2	49.0	52.7
50%	92.5	73.2	72.5
90%	153.7	149.8	145.7
FBP	184.5	181.0	181.5

2. THE USE OF ETHANOL IN DIFFERENT COUNTRIES

2.1. Prerequisites for the Literature Study

When the parameters of the literature survey for this project were considered it soon became apparent that the foci should be on the influence of adding ethanol on the vehicle and emissions (and thus its effects on the environment, air quality and health). Consequently, it was concluded that the following subjects should be examined during the search and discussed in the report:

- Vehicle performance/wear.
- Fuel.
- Vapour pressure.
- Emissions.
- Air quality and health effects.
- Life cycle analyses.

2.2. Fuel Ethanol in Sweden

Two sets of standards for fuel ethanol are presented here, one of which was developed by a small quantity ethanol producer in Sweden and one by the American Society for Testing and Materials (ASTM) as an industry standard.

The Swedish producer of ethanol, Svensk Etanolkemi AB (SEKAB) has presented specifications for fuel ethanol to be used when blending ethanol with gasoline, see Table 2.1 (SEKAB, 2004). The oil crises of 1973 and 1976 prompted a search in Sweden for alternatives to gasoline for light duty vehicles and a project was initiated to study the possibility of replacing some gasoline with an alcohol. Since a governmental investigation had been launched in 1965 in order to study an introduction of emission regulations it was also seen as the use of an alcohol blended gasoline could be one measure to reduce especially the emission of CO

To address practical issues associated with introducing an alcohol-based fuel a wide-ranging study was organized by the Swedish National Board for Technical Development (STU). Initially, this work was carried out by a small company named the Swedish Methanol Company, since it concentrated on the use of methanol as an additive to gasoline. Later, ethanol and other potential alternatives were included in the project and Sweden also became a member of the International Energy Agency (IEA). The company carrying out the work was then renamed the Swedish Motor Fuel Technology Co. (SDAB).

The work within the project included both laboratory and field tests. The results of laboratory investigations and field trials that had been carried out in various locations around the world were reported to the IEA in 1986 by STU and SDAB. (STU, 1986;1987). The countries that helped prepare the report were Canada, Japan New Zealand, Sweden and the USA. A great deal of valuable experience concerning the use of alcohol and (especially) alcohol blended gasoline was gathered during this co-operative assessment of alternative fuels. However, at this time Brazil was the only country in the world that was focusing on ethanol as an alternative to gasoline.

Table 2.1. Sales specification of technical ethanol 99.5% SPSE-Ethanol 99.5% 3 4 1 (1) 2004-11-03 SPSE-410.

Parameter	Limit		Method of analysis
Ethanol	% by volume % by weight	min 99.8 min 99.7	ASME 1112
Density	(D 20/4) g/ml	max 0.790	SS-ISO 758
Appearance	Clear, without particles		ASTM D 2090
Colour	Hazel	max 5	AMSE 1102
Water	% by weight	max 0.3	SS-ISO 760
Aldehydes (as acetaldehyde)	% by weight	max 0.0025	AMSE 1118
Acidity (as acetic acid)	% by weight	max 0.0025	AMSE 1114
Fusel oil	mg/l	max 50	AMSE 1107, GC-method
Methanol	mg/l	max 20	AMSE 1107, GC-method
Distillation interval*: - starting point - drypoint	 °C °C	 min 77 max 81	ASTM D 1078
Flashpoint*	°C	+12	SS-EN 22719
Explosion limits*	% by volume in air	3.5 - 15	Accepted from literature
Refractive index*	n_D20	1.3618	Accepted from Literature
Evaporation residue*	mg/l	max 10	AMSE 1124

*The seller guarantees these properties, although they are not tested on each delivery.

During the 1980s the focus of investigations and trials with alcohol fuels in Sweden switched to ethanol, both as an alternative for diesel oil and as an additive to gasoline. At this time the main rationale for introducing an alternative was to reduce exhaust emissions. Since the introduction of emission control systems with catalysts for gasoline-fuelled vehicles had efficiently reduced exhaust emissions, most of the research on alternative fuels in Sweden during the 1980s and 1990s was related to diesel-fuelled vehicles. Several comparative reports on different fuels, including alcohol-gasoline blends, were prepared, and the most comprehensive investigations are summarised and discussed in the following text.

In Sweden ethanol is currently used in the following three forms:

1. Blended in gasoline to a volume of 5 % according to the Swedish Petroleum Institute (SPI).
2. E85 in Flexible fuelled vehicles (FFVs).
3. E100 (including an ignition improver and other additives) for use in ethanol-fuelled buses.

2.3. *Fuel ethanol in the USA/California*

In the year 2000 the projected consumption of gasoline in the US was 127.568 milliard US gallons (468.897 million m^3), of which E10 accounted for 908.700 million gallons (ca 3.440 million m^3) and the consumption of MTBE in gasoline amounted to 2.1115 milliard gallons (ca 11.780 million m^3) according to the US department of energy (Yacobucci and Womach, 2000), see also Table 2.2. Since MTBE blending will be out by the end of 2005 according to MathPro (2002) there will be a need to increase the use of ethanol blended gasoline. According to

MathPro "The mandate volume would increase on an annual schedule, reaching 5 billion gallons per year (bgy) in 2012" of ethanol. Thereafter, annual mandate volumes would be set to maintain the percentage share of the U.S. gasoline pool that ethanol held in 2012".

Table 2.2 Estimated US Consumption of Fuel Ethanol, MTBE and Gasoline (Thousand Gasoline Equivalent Gallons), (Department of Energy,1998).

	1994	**1996**	**1998**	**2000 (projected)**
E85	80	694	1,727	3,283
E95	140	2 699	59[a]	59
Ethanol in Gasohol (E10)	845 900	660 200	916 000	908 700
MTBE in Gasoline	2 108 800	2 749 700	2 915 600	3 111 500
Gasoline[b]	113 144 000	117 783 000	122 849 000	127 568 000

The US Renewable Fuels Association (RFA) has presented industry guidelines for the use of ethanol in the American market and according to the Association the guidelines represent "a compilation of the key technical aspects of fuel grade ethanol use based on the collective experience and expertise of our member companies" (Renewable Fuels Association, 2002).

The following industry standard is valid as the industry standard for fuel ethanol to be blended in gasoline to any rate in the USA, Table 2.3.

Table 2.3. Industry standard for fuel ethanol to be blended in gasoline in the US.

ASTM 4806		
Property	**Specification**	**ASTM Test Method**
Ethanol, vol%	92.1	D5501
Methanol, vol%	0.5	
Solvent-washed gum, mg/100 ml max	5.0	D381
Water content, vol%, max	1.0	E203
Denaturant content, vol%, min	1.96	
Denaturant content, vol%, max	4.76	
Inorganic chloride content, mass ppm (mg/L), max	40 (32)	D512
Copper content mg/kg, max	0.1	D1688
Acidity (as acetic acid, mass-% (mg/L), max	0.007 (56)	D1613
pH	6.5 – 9.0	D6423
Appearance	Visibly free of suspended or precipitated contaminants (clear & bright)	

In the cited report the RFA gave certain recommendations and discussed a number of effects linked to the use of ethanol blended gasoline. The producers of ethanol and member companies of the RFA were recommended "to add corrosion inhibitors to all of their fuel grade ethanol at a treat rate to provide corrosion protection" comparable to the treatments applied to fuels such as neat gasoline

According to the RFA adding ethanol will affect several properties of gasoline, including its octane number, volatility, water solubility and oxygen content (the oxygen content of ethanol is approximately 33 % by weight). The octane numbers of ethanol quoted in various reports and other data sources differ, but in the cited paper from RFA (Renewable Fuels Association, 2002) the blending research octane number (RON) of ethanol is 129.0 and the blending motor octane number (MON) 96.0. Chevron has also reported that ethanol has a "Blending Research Octane Number (BRON)" of 129 (Chevron, 2002-2005).

An issue that should be addressed is whether (and if so, to what degree) the octane numbers will increase when blending ethanol in gasoline, and here too opinions differ. In the paper from RFA it is stated that the octane numbers (R+M)/2 will increase by 2 to 3 units.

Since fuel ethanol has a higher octane number than gasoline it may well be true that adding ethanol to gasoline increases the octane number, and thus improves the performance of the vehicle. However, there is considerable uncertainty about the extent to which the engine power will improve and whether this improvement will occur across the whole range of ethanol contents in gasoline. During an experimental investigation of ethanol blends in gasoline Abel-Rahman and Osman found that the maximum engine indicated power improvement occurred with a 10 % ethanol blend when adapting the compression ratio of the engine to the fuel Abel-Rahman and Osman, (1997). Performance tests were carried out when using different percentages up to 40 % of ethanol in gasoline.

Maintaining the safety of the working environment is an important issue when working with automotive fuels. In its Industry Guidelines, Specifications, and Procedures, the RFA recommends that ethanol should be handled "with the same safety precautions as gasoline" and that sparks and flames should be avoided when handling ethanol. A further recommendation is to "wear safety goggles when handling ethanol" Renewable Fuels Association, (2002). In addition, a guidebook released by the US Department of Energy (DOE) recommends that skin and vapour contact with E85 should be avoided and that ethanol-resistant gloves should be used (US Department of Energy, 2001). Further valuable information on many aspects of using alcohols in gasoline can be found in literature from the USA/California, where experience in their use (especially ethanol) and test data (both laboratory and field based) have been gathered over a long time. Unfortunately, however, few reports on measurements of emissions obtained when using ethanol blended gasoline have been found.

Progress towards the use of alcohol-gasoline blends as fuels has been underway since at least the 1970s, according to a report by Launder (2001). The Arab countries' embargo in the 1970s against the USA was the main factor that initially prompted use of alcohol fuels (ethanol and methanol) as substitutes to compensate for the resulting drop in gasoline supplies. An Energy Tax Act was passed, exempting 10 % ethanol-gasoline blends from the 4% gallon tax on motor fuels applied at the time. In the 1980s three additional Acts were passed that promoted production of ethanol from corn, *inter alia*, and these measures were reinforced by a "blender's credit" of 40 cents per gallon. It should be noted that the big automobile manufacturers Chrysler, Ford and GM were in favour of the E10 (gasohol) and they stated that its use would be covered in their vehicle guarantees, a move that was subsequently followed by almost all manufacturers.

Since the environmental protection authorities also favour the use of ethanol blended gasoline it has became common in US to blend 10 % ethanol in commercial gasoline. The Clean Air Act of 1990 mandated the use of reformulated gasoline (RFG) in certain areas of the USA to ameliorate air quality problems, such as high ozone levels, and the use of oxygen blended fuel in areas with high levels of carbon monoxide during the winter. In order to meet the demand for ethanol as a blending component a 1-psi waiver in the permitted vapour pressure parameter (RVP) has been allowed for ethanol-gasoline blends, although it has been shown that ethanol will raise the vapour pressure of the fuel. An increase in vapour pressure has been shown to increase the emissions of VOCs (volatile organic components), which may in worst case scenarios result in enhanced levels of ozone (US EPA, 1993). Therefore, the EPA has argued that no waiver should be applied, as can be seen in the following quotation: "EPA believes that ethanol can and will play an important role in reformulated gasoline without a 1.0 psi waiver, and that granting such a waiver would therefore be unreasonable" (US EPA, 1993).

At the end of 2001 "A bill to amend the Clean Air Act to address problems concerning methyl tertiary butyl ether, and for other purposes" was introduced to the US Senate concerning reformulated fuel. In a summary of the bill the following seven amendments (abbreviated here) were recommended to the Senate:

- Actions should be taken concerning the leakage of MTBE from corrodible underground tanks, which represents a risk for public health, welfare and the environment and inspections of underground tanks should be carried out.
- The Clean Air Act should authorize any State "for which a waiver is in effect to impose control of any fuels and fuel additive for the purpose of water quality protection. Requires the Administrator of the Environmental Protection Agency to ban the use of MTBE in motor fuel within four years of this Act's enactment".
- The State Governor should be authorized, "upon notification" of the EPA Administrator, "to waive oxygen content requirements for reformulated gasoline other than those regarding oxygen content to be reformulated gasoline". This "Requires regulations to: (1) ensure that toxic air pollutant emissions reductions achieved under the reformulated gasoline program are maintained in such States; and (2) establish performance standards".
- The amendments require the Administrator to: (1) carry out tests in order to evaluate health and environmental effects of the use of fuel and fuel additives. Furthermore, tests should be carried out in order to study the effects of using MTBE and other ethers which may be used to replace MTBE; (2) to publish analysis showing changes of the air quality resulting from implementation of the Act; (3) to complete a model which reflects the effects on the emissions that are related to the characteristics or components of the fuel used during 2005.
- The Act eliminates the waiver that allows higher RVP limits for ethanol blended gasoline.
- "Allows State implementation plan revisions that apply conventional gasoline prohibitions to non classified areas".
- The Act also authorizes "grants to MTBE merchant producers to assist in conversion of production facilities to the production of other fuel additives. Authorizes appropriations" (US Senate 2001).

2.4. Fuel Ethanol in Japan

It has been difficult to find information on investigations carried out in Japan concerning the introduction and use of ethanol in either neat or blended forms. One reason for this is that interest in ethanol has been low in Japan. Another is that the few relevant reports that have been found have nearly all been written in Japanese.

However, Japanese interest in alternative fuels has been concentrated for many years on natural gas or liquid fuels that could be produced from natural gas, such as methanol and DiMethyl Ether (DME). In recent years Japan has also shown increasing interest in so-called synthetic fuels, such as paraffin (synthetic diesel) and (to some extent) alkylate (synthetic gasoline) fuels produced from natural gas (and maybe in the future from gasified biomass) by the so-called Fischer-Tropsch technique.

In the last few decades methanol has been the main Japanese alternative to gasoline. However, according to some unconfirmed reports and personal communication with Jan Lindstedt, The Swedish Bioalkohol fuels Foundation, BAFF, Japan has started to introduce ethanol and is currently planning to increase its use.

2.5. Fuel ethanol in Brazil

In a paper released by the Brazilian embassy in India information about the national program for fuel alcohol in Brazil (PROALCOOL) can be found (Brazilian Embassy, 2002). According to this paper, the program that initially introduced the use of ethanol as an automotive fuel in Brazil started in 1974 "as a consequence of the oil crisis". Sugar cane plantations introduced by the Portuguese in the 16th century were, and still are, used as sources for the ethanol production.

One of the main requirements linked to the introduction of PROALCOOL was that there should be close coordination amongst the authorities and other parties involved, namely "the Ministry of Agriculture and sugarcane planters, the Ministry of Science and Technology and research centres, the Ministry of Industry and Commerce, the automobile industry, Ministry of Mines and Energy, PETROBRÁS (state owned oil company), the fuel distributors, and the gas stations, the Ministries of Finance and Planning and, last but not the least, the automobile owners". There was also a requirement that subsidies should be used to stimulate the production of cars to be run on alcohol, and the relaxation of tax on industrialised products is seen to have been effective in this context.

An important benefit of the program is that it has provided stable employment for approximately 500 000 workers in the sugar cane plantations and similar numbers in the alcohol/ethanol production industry and other activities connected to the use of ethanol fuels such as transportation, blending etc.

There have also been considerable benefits in terms of greenhouse gas reductions since ethanol produced in Brazil is exported to and used in many countries, especially India, Japan, China, Thailand and Australia. A certain amount is also exported to Sweden and blended in gasoline.

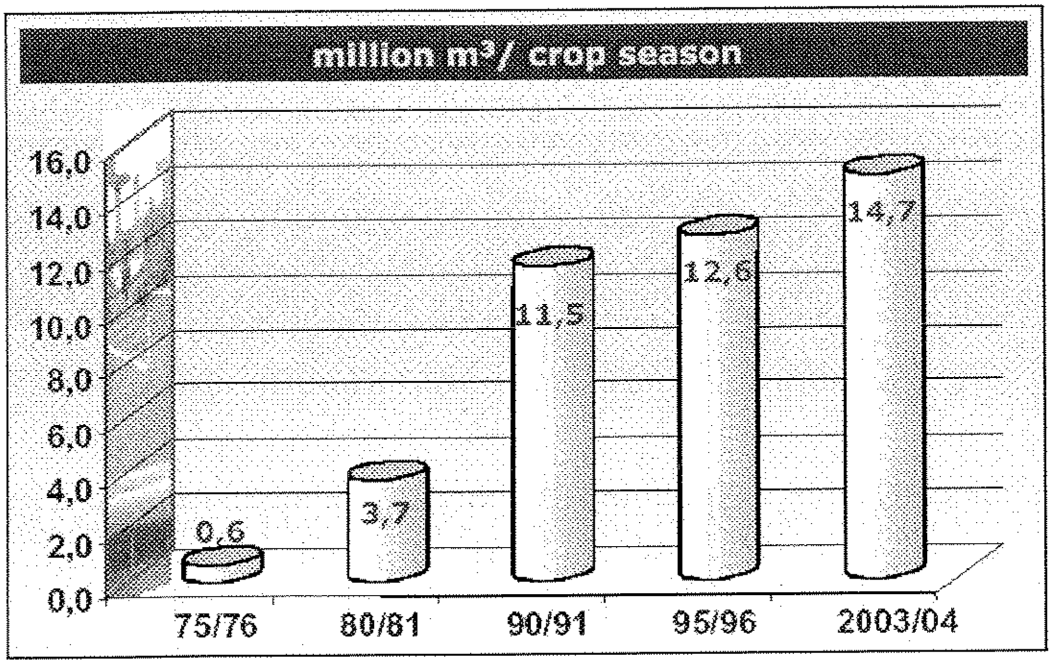

Figure 2.1. Growth in ethanol production (anhydrous and hydrous) in Brazil from 1975/76 to 2003/4.

In a workshop on Mitigation (SBSTA 21/COP in December 2004 in Buenos Aires Alfred Szwarc (a consultant at the Ministry of Science and Technology) described Brazilian experience with fuel grade ethanol. He noted that two types of ethanol fuels - anhydrous (min. ethanol content 99.58 %) and hydrous (ethanol content 95.13 – 95.98 %) - are produced under Brazilian regulations. Anhydrous ethanol can be blended with gasoline up to 25 % by volume while hydrous ethanol is used either as a neat fuel or blended with gasohol (see section 13 for the definition of gasohol) for use in FFVs (Szwarc, 2004).

Unfortunately, few papers prepared in Brazil and written in English have been found. Therefore, the effects that ethanol-gasoline blends with up to 25 % ethanol contents have had on the drivability, deterioration and wear of vehicles and last (but not least) the emissions and air quality in urban areas are not clear.

According to Szwarc, the use of ethanol as a blending component has increased over the years and the content of ethanol in Brazilian gasoline blends has increased from 4.5 % by volume in 1977 to 25 % in 2002, as shown in Figure 2.2. However, today more than 4.2 million cars are ethanol-powered according to data and information presented by Online TEFL. Of these, about 40 % are passenger cars and in total the 4.2 million vehicles annually consume approximately 14 million m^3 of ethanol (Ethanol Curriculum Online TEFL Module 5, 2005).

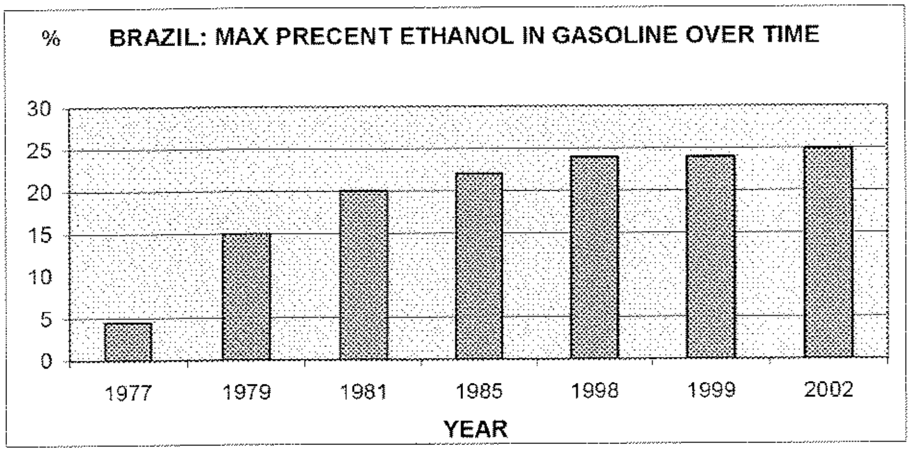

Figure 2.2. Changes in the maximum ethanol content of ethanol-gasoline blends in Brazil, 1977-2002 (Szwarc, 2004).

No actual data from emission tests in Brazil have been found, but the following observations were made by Szwarc (2004) at the workshop in Buenos Aires.

"Vehicle Emission Reductions Related to Fuel Ethanol Use in Brazil:

- Lead additives banned since 1990.
- Reduction of SOx.
- Reduction of PM (carbon and sulfate particles).
- VOC's with lower toxicity & photochemical reactivity.
- CO: Higher reduction in older E100 (up to 70%) and gasohol (up to 40%) vehicles in comparison with ethanol-free gasoline".

2.6. *Fuel Ethanol in East Asia*

In addition to Japan several other countries in East Asia, including China, India and Thailand, are investigating the effects of using ethanol blended gasoline on the environment, vehicles and other issues. These countries have good opportunities to start ethanol production on varying scales.

China

In 2001 the Chinese State Development Commission launched an ethanol program and after careful consideration issued quality standards for denatured ethanol and ethanol blended gasoline. In the same year Beijing (China) also organised a World fuel ethanol congress (2001).

It is well known that there is an urgent need to improve the air quality in China, especially in Beijing, and when it launched the program the Chinese government announced that "China plans to spend nearly $12 billion on a program to cut smog and pollution in Beijing by 2008. This emphasises one of the reasons for the large-scale introduction of ethanol, and when launching the program it was also said that "China may soon become an ethanol industry leader..." The program for the Congress also indicates that this event was considered a platform for initiating use of ethanol as an automotive fuel on a broader scale (Beijing World Fuel Ethanol Congress 2001).

In China ethanol is commonly produced from corn and sorghum (Nan et al., 1994). According to the Beijing Times, China is "pushing" the use of ethanol as fuel by constructing a plant in the Henan province that will produce 300 000 tons of fuel per year (Beijing Times, 2002). A headline in the Beijing Times also stated that "China Promotes Ethanol-Based Fuel in Five Cities". Otherwise, this should be changed to 'The Beijing Times has also reported that China is promoting the use of ethanol-based fuel in five cities". These five cities are Zhengzhou, Luoyang and Nanyang in Henan province and Harbin and Zhaodong in Heilongjiang province, northeast China (Beijing Times, 2002a). In order to force motorists to use fuel ethanol, all vehicles carrying a licence plate starting with "Yu A" have to use ethanol-based fuel according to an order by the Zhengzhou Municipal Government. The specification of "ethanol-based fuel" is not clear, but in another paper it is said that ethanol will be blended with lead-free gasoline in a 1:9 ratio (US Commercial Service, 2003). In the province of Liaoning new regulations state that car owners must use ethanol as a fuel for their vehicles. If they do not switch to ethanol they will be fined between 5,000 yuan (US$600) and 30,000 yuan (US$3,600) since "Ethanol fuel can play an important role in easing consumption of traditional petrol and protecting the environment" according to the Liaoning Development and Reform Committee (People's Daily, 2004).

India

In India, like other countries around the world, there was a considerable shortage of oil and sharp rises in crude oil prices in the 1970s, prompting interest in fuel ethanol. In India too, plans have been developed to use ethanol-gasoline blends (Uppal, 2002; Bhanot and Chaudhari, 2003), and even ethanol-diesel oil blends (Acharya et al., 2002).

Based on recommendations by a committee for the development of alternative fuels for motor vehicles, trials were carried out in New Delhi in 1991. The test fleet included 93 vehicles and comprised cars, vans and jeeps. The fuels used were blends of 5 % and 10 % ethanol in gasoline. The results of the field trials are summarised in the following quotation:

- "93 Delhi Admn. vehicles logged 1.787 milj km.
- Saving of around 20 m^3 of scarce gasoline.
- Cooler and smoother operation of vehicles.
- No adverse effect on engine oil.
- Reduction in CO and HC emissions.
- Overall fuel economy is comparable with neat gasoline operation" (Malhotra, 2001).

There seems to have been a lull in the development of fuel ethanol in India during the 1990s. However, according to the available literature considerable activity is now underway.

Since the authorities in India found that the agriculture sector needed support and that air quality had to be improved the Ministry of Petroleum and Natural Gas Resolution started to examine issues related to the introduction of ethanol blended gasoline. According to the specifications set by the Bureau of Indian Standards for Gasoline up to 5 % ethanol can be blended with gasoline (The Gazette of India, 2002). In addition, Winrock International India* initiated the formation of

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*Winrock International India (WII) is a non-profit organization working in the areas of natural resource management, clean energy and climate change.

an "Ethanol Coalition of India" in 2000 to promote the development of fuel ethanol (Mishra, 2002).

Thailand
In the autumn of 2002 Thailand hosted the 14th ISAF International Symposium on Alcohol fuels, entitled "The Role of Alcohol Fuels in Meeting the Energy, Environmental and Economic Needs of the 21st Century". At this symposium many papers prepared in Thailand were presented, some of which gave information on the development of fuel ethanol production in Thailand. In addition a number of relevant papers reporting investigations and other activities in Thailand have been found in Internet searches.

In November 2001 the RFA reported that the Government of Thailand had approved the use of a 10 % ethanol/gasoline blend in order to increase the production of ethanol in the country. One reason why the government wants to increase the content of ethanol in gasoline is the need to be less dependent on imported oil and to promote the use of domestically produced energy carriers (Renewable Fuels Association, 2001). It has also been reported that there is an attempt in Thailand to replace MTBE by ethanol (World Association of Beet and Cane Growers, 2001). One way to stimulate this replacement is seen to be a plan to decrease the excise tax on ethanol mixtures.

According to the literature there are five or six main potential sources of ethanol in Thailand, including sugar cane, molasses and cassava (Ethanol Industry in Thailand, 2004) and sweet sorghum (Thanonkeo et al., 2002). The scope for producing ethanol from sweet sorghum has been investigated via a process presented by Thanonkeo et al . In addition, production of ethanol from bagasse and rice straw has been studied by Siwarasak and Wirivutthikorn (2002).

2.7. Fuel Ethanol in Australia

In a literature review prepared by the Orbital Engine Company (2002a) for Environment Australia it is reported that the first Australian examination ("trial") of a blend of ethanol (15%) in gasoline was carried out from 1980 to 1983. There was then a long time lag to the second trial, which was conducted in the years immediately preceding 1998 with a 10 % blend of ethanol in gasoline. The 10 % figure seems to have been related to the situation in the USA, since the American car manufacturers agreed to accept a blend of up to 10 % ethanol in gasoline without changing the warranty conditions of their vehicles.

This is also reflected in a paper presented by Dr. Kemp (the Australian Minister for the Environment and Heritage), where it is stated that "The major automobile manufacturers have advised my Department that they accept the use of 10 per cent ethanol blends and that such blends will not affect vehicle warranties," (Ministry for the Environment and Heritage, 2003) According to the paper and other reports from Australia there is interest in blends with higher alcohol contents, and investigations have been carried out with blends of up to 20 % ethanol in gasoline and some conclusions from these investigations will be discussed below (Orbital Engine Company, 2003; 2004). The main results from these tests have been presented in comprehensive summaries in the cited reports.

In 2004, the ethanol production capacity in Australia amounted to 135 000 m^3. Of this, around 55 000 m^3 was used for blending with gasoline. About 30 – 35 000 m^3 was exported for other purposes and the rest was used domestically, but not as an automotive fuel. There are plans to increase the production capacity of fuel grade ethanol incrementally by about 270 000 m^3, in total, by building three new production plants. An interim production target will be half of this amount. However the production of 270 000 m^3 of ethanol, less than the 360 million litres required to supply ethanol for an E10 blend in Queensland alone. (Boswell, 2004).

Today, ethanol is produced from sugarcane and wheat, but the possibility of using other feedstocks (such as barley, corn and sorghum) is discussed. There is also interest in producing ethanol from other biomaterials, such as wood, i.e. lignocelluloses (Cheung et al., 2003).

The discussion about fuel ethanol in Australia has heavily focused on two issues: future gasoline quality standards and labelling of the gasoline pumps.

In September 2000 a paper entitled "Setting National Fuel Quality Standards" was released by the Natural Heritage Trust on the "Proposed Standards for Fuel Parameters (Gasoline and Diesel)" and the "Revised Commonwealth Position". One of the main positions taken by the Commonwealth was that the oxygen content in gasoline must be higher than 2.7 %, as proposed in the standards for gasoline, to allow the continued use of a 10 % ethanol-gasoline blend already available on the market. The proposal by the Commonwealth was that an exemption should be made for ethanol so as the standard could be the following when referring to "Summary of revised Commonwealth proposal for fuel quality standards" where the specification for gasoline is: "Oxygen content: 2.7 % (max) with an exemption for ethanol blends up to 10 %" (Natural Heritage Trust, 2000).

Noting the Commonwealth position, Environment Australia published a paper entitled "Setting the Ethanol Limit in Petrol" which officially invited the public to send in their views on the limit for ethanol blends in gasoline (Environment Australia, 2002).

After years of discussions, in which representatives of the petroleum industry, the Australian Automobile Association (AAA), various gasoline suppliers and the insurance company NRMA* (which covers cars *inter alia*), have been involved (the authors of this report conclude that NRMA is not willing to cover the risk for damage to cars that may be caused by a high percentage of ethanol in gasoline). The outcome of these discussions prevented Environment Australia (and thus the Government), from allowing higher alcohol contents than 10 % in blends with gasoline. NRMA has also been conducting research on ethanol gasoline blends used in motor vehicles (Australia Automobile Association, 2002; 2002a; NRMA, 2003) and found that there could be problems with higher alcohol contents. A study conducted by Apache Research Ltd. for NRMA showed that 10 % ethanol could be accepted, but the use of a 20 % blend led to increased wear (see section 3.1, below).

All those who were strongly opposed to higher ethanol contents than 10 % supported the 10 % limit and, in fact, welcomed the opportunity to use gasoline with that of blended ethanol. The AAA says that they support ethanol contents in gasoline of up to 10 %, and the policy of labelling ethanol blends at the gasoline pump. The opinion of the NRMA has been that no higher ethanol content than 10 % should be allowed "until comprehensive research shows that it will not damage fuel systems and engines" (Australian Automobile Association 2002; NRMA, 2002;

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* National Roads and Motorists' Association

2002a). In a paper presented in 2003, Shell notes that the Australian Institute of Physics* (AIP) has been "taking positive steps towards achieving the Government's [350 000 m^3] target for bio fuels" by participating in various activities related to the further introduction of bio fuels, including ethanol. The position of the AIP is that the introduction of ethanol under the government policy should be viable if the consumers feel confidence in its use as a fuel (Shell, 2003). Early in 2003 BP announced that it had been delivering a 10 % blend of ethanol in gasoline, but was going to stop producing it since consumer confidence in ethanol blended gasoline was low (BP, 2003). In December 2003 BP announced that it will limit its marketing to a 10 % blended regular unleaded gasoline in Queensland after the middle of December 2003. However, Dr George Nicolaides of BP, admitted that ethanol blended gasoline fuels "have a role to play in Australia as a renewable fuel and as an octane enhancer" (BP, 2003a).

The actions taken by the petroleum industry, the AAA and NRMA obviously created pressure on Environment Australia and the Australian government since it resulted in the Minister for the Environment deciding to set a 10 % limit for ethanol blends in gasoline in April 2003. He also announced that he was going to appeal to the State Governments to require labelling at fuel pumps delivering ethanol blends (Federal Government, 2003; Federal Government, 2003a).

The decision taken by the Minister for the Environment is explained in papers released by the Ministry. One of the papers states that "ethanol blends for the Australian market means gasoline that, as tested in accordance with the Fuel Standards (Gasoline) Determination 2001, contains more than 1% ethanol". It is also stated that "the ethanol blend may contain up to and including 10% ethanol; and a statement that the ethanol blend is the subject of this standard" (Kemp, 2003). In a second paper the standards for some of the fuel parameters are presented and in a third paper the labelling requirements are listed and it is stated that "If you sell an ethanol blend you will have to display a label" (Department of the Environment and Heritage, 2004 and 2004a). When delivering blended fuel from a pump the label must be displayed "as close as practicable to each nozzle that dispenses the ethanol blend and for retail supply special requirements are to be followed". In Figure 2.3 a replicate of the label is shown.

Preparation of the position paper for the "Fuel Quality Standards Act 2000" (Office of Legislative Drafting, Attorney-General's Department 2004) has started, and the Department of the Environment and Heritage has invited stakeholders to send in comments by by close of business, 18 February 2005 (Department of the Environment and Heritage, 2004a). A background paper for "Setting a Quality Standard for Fuel Ethanol" has been prepared by Hart Downstream Energy Services (Hart Downstream Energy Services, 2004).

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* Australian Institute of Physics (AIP has gained recognition as a key representative body of Australia's petroleum industry).

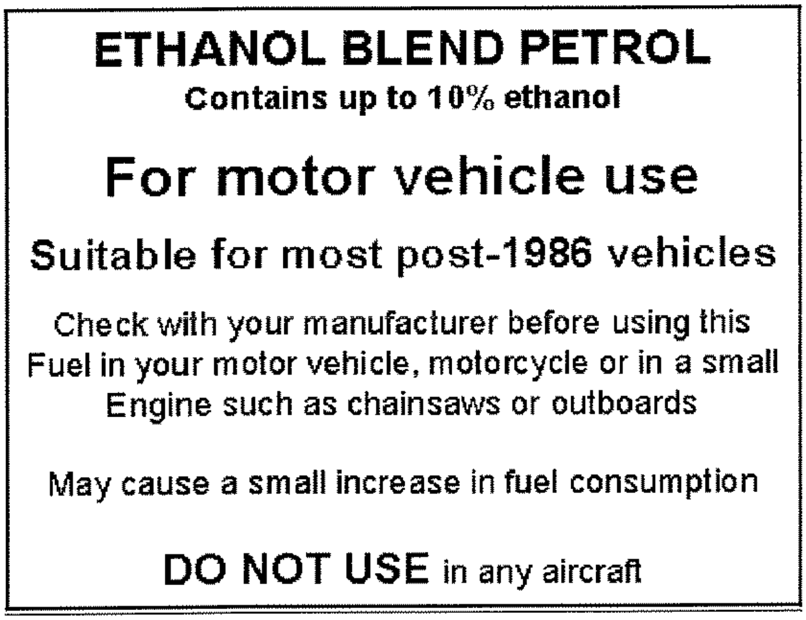

Figure 2.3. The Australian label for ethanol blended gasoline. (Department of the Environment and Heritage, 2004a).

3. DATA AND EXPERIENCE

Data and experience related to the use of ethanol blended fuels are presented and evaluated. The materials selected for examination were largely reports and other papers presented during the last 10 years. When searching via the internet a great number of papers can be found, so a second selection criterion, applied to web-sourced materials was to exclude all texts that were not in report format, even if they were based on empirical studies. However, many papers from various authorities, universities and institutions have been of great value even if they have not been written in the form of a report, since they provide information about decisions taken or to be taken and research that will be presented eventually. It should be noted that this project does not consider the production of ethanol, the supply and delivery of ethanol blended fuel or associated costs.

Papers from lobby organizations were also often excluded since they tend to be prejudiced and to present conclusions without giving sufficient information about the basic conditions and data on which the conclusions are based. When examining reports dealing with blended fuel, wear of the vehicles and vehicle performance it soon becomes apparent that opinions differ among those concerned with the use of ethanol and the impact on vehicles of using ethanol. Data on air quality, health effects and emissions linked to the use of ethanol blended gasoline, are presented and discussed in two separate sections, 4 and 5, below.

3.1. Vehicle Performance

One of the objectives for this project is to find out whether it is possible to increase the content of ethanol in Swedish gasoline from about 5 % to a higher percentage without creating problems that would be unacceptable to the car manufacturers, cars owners and/or drivers. However, experience and data obtained in empirical studies have shown that the use of ethanol contents up to 10 to 15 % in gasoline should not create any serious wear of the vehicle/engine, but may influence drivability.

A comment on World Wide Fuel Charter (WWFC) was that WWFC should increase the maximum oxygen content in gasoline to 3.5% (by mass) in order to allow a blend of 10% ethanol in gasoline (WWFC, 2002; WWFC Comments, 200)

The response from WWFC is that the WWFC Committee selected a limit of 2.7 % as the general mass of oxygen in gasoline in order to assure correct operation of the engine. However, a footnote to this statement indicates that the Committee accepts the use of 10% ethanol in gasoline if the fuel conforms to the requirements set for the fuel.

Furthermore, the position of WWFC is that the level of 3.5% oxygen content for ethanol blends in gasoline is too high. There is a WWFC requirement for using co-solvents and inhibitors when methanol is used.

Due to the maximum oxygen level in gasoline WWFC do not allow an addition of 10% ethanol to gasoline which may already contain 2% MTBE despite the fact that this is allowed by US EPA. (WWFC, 2002; WWFC Comments, 200)

The Orbital Engine Company in Australia has carried out extensive tests for the Australian government on vehicles fuelled with ethanol blended gasoline, focusing especially on its effects on the durability of their components (Orbital Engine Company, 2004)

- A Holden Commodore VN, 1990 model, which has an electronic fuel injection system, a three-way catalyst, a closed loop control system and runs on ULP ("unleaded petrol") gasoline.

- A Ford Falcon XE, 1985 model, which has electronic fuel injection, open loop control systems and runs on LRP (low vapour pressure) gasoline.

- A Holden Commodore VK, 1985 model, which has a carburettor and runs on LRP gasoline.

According to the Orbital report the tests followed, as closely as possible, standard SAE protocols (J1748 for polymeric material, J1748 for metallic material and J1681 for material/component immersion testing). A 20 vol% ethanol gasoline blend was used as test fuel. The results from the 2000 hour testing and evaluation program can be summarized as follows:

- Metallic fuel system: various parts of the fuel system such as the fuel pump, the fuel injectors, metallic parts of the fuel regulator diaphragm, and the fuel pressure regulator showed corrosion, tarnishing and pitting.
- The fuel tank metal, the fuel sender unit, and the PCV valve/spool showed corrosion and pitting, tarnishing and the plastic filters were discoloured.
- Various parts of the carburettors and associated components of the carburettor-equipped car showed corrosion, pitting and tarnishing.

The general view derived from studying the international literature is that blends with up to 15 % ethanol do not have any serious effects on the performance and wear of the vehicle. Many reports and other documents deal with the use of ethanol, including its effects on performance and wear, but the most extensive reports focus on flexible fuel vehicles (FFVs), i.e. vehicles designed to be fuelled with up to 85 % ethanol in gasoline.

Car owner/driver acceptance of a new fuel, e.g. a fuel with a certain level of an alcohol in gasoline, is highly dependent on the cost of the fuel and the performance of the vehicle. Concerning drivability: "The most important aspect of performance (other than starting) is acceleration, both from a stop and at highway speeds in order to pass" and is a vital issue for customers according to McLean and Lave (2002). In the Science Fair Projects Encyclopedia (2004) it is said that both of the ethanol-gasoline variants "E10 and "E15", containing 10 % and 15% ethanol in gasoline, respectively, are "generally safe" for common usage in automobile engines. Adding a higher percentage of an alcohol like ethanol may affect the performance of the vehicle, especially its starting and drivability at low temperatures. These effects on the engine and vehicle may also result in increased emissions, due to sub-optimal operation of the vehicle's emission control systems during the time lag until the engine and catalyst reach the normal temperature for a continuously running engine. However, ongoing development of engines and control systems for the fuel and emissions have resulted in considerable improvements related not only to emission performance but also to drivability. Further advances may solve some of the problems concerning the cold start parameters of the engines, thus improving their start-ability and emission performance when used with ethanol-gasoline blends. Although vehicle performance and wear of the engine and its control systems are linked to a number of different factors, of varying importance, many significant steps have been taken in recent years which will reduce these problems.

3.2. *Cold Starts and Driving*

High levels of an alcohol (over 20 %) usually adversely affect cold starts and warming up in low temperature conditions since more heat is needed to vaporize alcohol than gasoline. Normally low levels, < 10 %, of alcohols in gasoline do not cause problems during cold starts and the warming-up phase of the engine, especially for modern vehicles (US Department of Energy, 1991).

Several methods and devices are available to improve the cold start and emissions during the warming up period. One recommended for use with FFVs is a specially designed catalyst presented by the National Renewable Energy Laboratory (NREL). A key feature of the catalyst tested by NREL is that it is insulated with a "Variable-conductance vacuum insulation" (NREL, 1996). Another suggestion is to use certain additives in the fuel, but this does not seem to be a good alternative for ethanol-gasoline blends with low alcohol contents. In Sweden an engine heater is commonly used to improve the cold starts and warming up of the engine.

3.3. *Impact of Fuel*

In the RFA (2002) paper the impact of adding ethanol to the base fuel on the physico-chemical properties of the fuel is also discussed. The properties considered are fuel volatility, vapour pressure, distillation properties, calculated drivability index, and vapour lock protection index in six classes (according to ASTM D 4814), oxygen content, water tolerance and gasoline additives. The following paragraphs summarise the impact of adding ethanol on these variables, as discussed in the paper.

Fuel volatility: Adding ethanol to gasoline will increase the volatility, decrease the 50 % distillation point (T_{50}), and affect both the drivability index and vapour lock protection.

Vapour pressure: This is a measure of "front end" volatility, and a fuel with extremely high vapour pressure may cause problems with hot start ability, hot drivability and vapour lock.

Distillation properties: Ethanol in gasoline will reduce the T50 value of the fuel, which may cause problems with older vehicles in warm weather. It has been shown that later models of fuel injected vehicles are less sensitive to a reduction in T50 than older cars.

Drivability index: The drivability index is based on the relationship between the distillation temperature of the fuel and the cold start and warming up parameters of the vehicle. The following formula can be used to calculate the drivability index (DI):
$DI = 1.5\ T_{10} + 3.0\ T_{50} + 1.0\ T_{90}$

Vapour lock protection index: ASTM D 4814 defines six classes of vapour lock production, as shown in Table 3.1.

Table 3.1. ASTM D 4814 Vapor Lock Protection Class Requirements (Oak Ridge National Laboratory, 2002).

Vapour Lock Protection Class	Vapour/Liquid (V/L)*#	
	Test Temperature °C	V/L, max
1	60	20
2	56	20
3	51	20
4	47	20
5	41	20
6	35	20

* At 101.3 kPa pressure (760 mm Hg.)
#The mercury confining fluid procedure of test Method D 2533 shall be used for gasoline-oxygenate blends. Test Method D 5188 may be used for all fuels. The procedure for estimating temperature-V/L may only be used for gasoline
(ASTM D 4814e).

The definition according to the ASTM standard ASTM D 4814 is that the Vapour Lock Index, according to the ASTM standard ASTM D "is the ratio of the volume of vapour formed at atmospheric pressure to the volume of fuel tested in Test Method D 2533" (Renewable Fuels Association, 2002). As can be seen in Table 3.1, test method D 2533 is to be used for oxygenate-gasoline fuel blends. The requirement for each of the classes is that the maximum vapour to liquid ratio formed at the test temperature (TV) must be at most 20 (Oak Ridge National Laboratory, ORNL, 2002), as shown in the table. The vapour lock protection index is defined as TV/L20, meaning that higher TV/L temperatures are required for summer grades of ethanol-gasoline blends and lower TV/L20 temperatures are required for winter grade blends, which are more volatile. The ORNL has presented two examples, one of which is related to vapour lock protection class 1, which would have a TV/L20 temperature of 60°C while class 6, which is more volatile would have a TV/L20 temperature of 35°C.

In practice this is reflected in the fact that the RVP standards for winter and summer grade gasoline in Sweden are 95 kPa and 70 kPa, respectively, and that the vapour lock class depends not only on the climate but also the altitude. A salient issue to consider is whether a 10 % ethanol content in Swedish summer gasoline would meet the ASTM vapour lock protection standards. The authors of this report strongly believe that adding 10 % ethanol to Swedish winter grade gasoline would not create any problems in meeting the ASTM vapour lock protection standards.

Oxygen content: The standard for the oxygenate content in gasoline is set on a weight basis, as can be seen in Table 3.2 (Renewable Fuels Association, 2002).

Table 3.2, Ethanol content and oxygenate content in fuels.

Fuel ethanol content, volume %	Fuel Oxygen Content, weight %
5.7	2.0
7.7	2.7
10	3.5

Since there are differences in the density of different grades of gasoline compared to the density of ethanol the final content of oxygen will vary if the blending volume is fixed to a certain volume.

Water tolerance: It is well known that ethanol has affinity to water, so appropriate measures must be taken when blending ethanol with gasoline and during the distribution of ethanol-gasoline blends. According to the RFA the water tolerance of blended fuels is temperature-dependent, i.e. the tolerance is lower at low temperatures. A 10 % ethanol blend in gasoline will tolerate approximately 0.5 % water (v/v) at temperatures of 15.5 °C or more, while the water tolerance is 0.3 % (v/v) water at approximately -12 °C (Renewable Fuels Association, 2002).

In a report prepared by Krause and finalized by Korotney the possibility of phase separation occurring in ethanol-gasoline blends contaminated with water has been discussed.. When phase separation occurs in a blend of ethanol in gasoline, water starts to remove ethanol from the gasoline and another phase, containing both ethanol and water, forms in addition to the gasoline and ethanol phase.. The impact of the water-ethanol phase on the engine is greater in a two-stroke engine than in a four stroke engine, were it may combust in the engine. In a two-stroke engine the ethanol-water phase will compete with the gasoline-oil mixture and reduce the lubricating ability of the lubricating oil. However, phase separation normally only occurs in the presence of liquid water in the ethanol-gasoline blend (Krause and Korotney, 1995).

In a study of a blend of anhydrous ethanol and unleaded gasoline the wear was not found to be unusually high (US Department of Energy, 1991). However, with 11 % water in ethanol a significant increase in the wear occurred, since the engine temperature was reduced. Formic acid and water vapour in the combustion gases during low temperature combustion of alcohols containing high percentages of water may oxidize metal components in the engine. The acidity of the combustion gases in combination with the lubricating ability of the lube oil will significantly increase the wear rate. It is well known that the concentrations of formaldehyde and acetic acid are relatively high in the combustion gases when methanol or methanol-gasoline blends are used in a combustion engine. However, certain amounts of these gases are also formed, in addition to considerable amounts of acetaldehyde and acetic acid, during the combustion of ethanol or ethanol-gasoline blends.

According to the US DOE, those who are responsible for delivering and blending alcohols in gasoline are aware of the risks and consequences of contamination of alcohol fuels by water. The possibility of increased wear of components in the engine is not the only risk, since water in the fuel can also adversely affect the start ability and driving performance of the engine. Methods for blending alcohols in gasoline are discussed in section 1.2. However, since the risk for water contamination of the fuel is a potentially serious problem Chevron in the US has decided to use ethanol only in areas where appropriate terminal facilities (i.e. where ethanol is properly distributed) are available, in order to ensure the quality of the blended alcohol-gasoline fuel (Chevron, 2004).

Gasoline additives: Various additives may be used in gasoline, such as detergent/deposit additives. For ethanol-blended gasoline the RFA recommends that ethanol producing member companies should "treat their ethanol with a corrosion inhibitor to ensure that any final blend is properly treated for corrosion protection".

The RFA has established recommendations for blending ethanol in gasoline, for storage tanks, for distribution, and at customer delivery points, for protecting pumps and meters. Many of these recommendations are certainly known by suppliers of ethanol blended fuels. However one of the recommendations is of great importance for those filling cars with ethanol blended gasoline, namely that: "When first converting to an ethanol program it is advisable to recalibrate meters after 10-14 days to ensure that the change of product has not caused any meters to over-dispense" (Renewable Fuels Association, 2002).

The effects of adding ethanol to gasoline on fuel properties have been discussed by Chandra Prakash in a report prepared for Environment Canada (Prakash, 1998). She notes, *inter alia*, the advantage of using ethanol as an enhancer of the octane number of the blended fuel. As an example she refers to a comparison (summarized in Table 3.3) of ethanol blended gasoline with neat gasoline.

Table 3.3. Ethanol and gasoline octane numbers.

Property	**Ethanol**	**Gasoline**
RON	102-130	90-100
MON	89-96	80-92
(RON+MON)/2	96-112	85-96
Blending RON	112-120	90-100
Blending MON	95-106	80-92

Her essential message concerning the octane number is that the high octane rate of ethanol increases the value of the blended fuel. She also points out that the higher octane number of the blended fuel confers advantages in terms of fuel efficiency for later models of vehicles since they are commonly equipped with knock sensors, which retard the ignition timing in the event of knocking. In such cases the fuel will be more efficiently matched to the engine.

The fact that ethanol has a lower heating value than gasoline may affect the performance of the vehicle, since the presence of an alcohol in gasoline will lean out the fuel, resulting in some loss of engine power. According to Prakash this is somewhat offset by the fact that adding ethanol to gasoline results in a higher volume of combustion gases, which increases the pressure in the cylinder and thus increases the power efficiency by 1 to 2 percent.

The negative effects of blending ethanol in gasoline in terms of increased volatility, enleanment (which affects the cold start ability), fuel economy and the water miscibility of ethanol are also discussed in the cited report (Prakash, 1998). These effects have been discussed in other sections of the present report, but not the risk for deposits forming in the engine caused by cold starts at low temperatures. Additives compatible with the engine oil must be used in order to avoid deposits building up.

Besides -pollution from exhaust emissions there are also issues related to the handling of ethanol/gasoline blends, for instance their storage in underground fuel tanks and the potential contamination of groundwater due to leaks, which are addressed in a number of reports. Powers et al. (2001) state that several modelling studies predict that the presence of ethanol in gasoline will probably increase the BTEX (i.e. benzene toluene, ethylbenzene and xylene) plume from a leakage. According to Deeb et al. (2002) and Lovanh et al. (2002) simulations indicate that the benzene plume is likely to increase by 16 to 34% in the presence of ethanol. Neither the true extent of the potential increase nor the risks for leakage to the ground soil have been well characterised. In addition there are indications in the reports that biodegradation of benzene is severely inhibited by the presence of ethanol.

3.4. *Impact of Lube Oil*

During the survey of the international literature no report was found that specifically recommended the use of special oil when driving vehicles with up to 10 % ethanol in gasoline. For FFVs some vehicle manufacturers claim that a special lubricating oil is needed (still, see under section 3.6). However, according to information from the National Ethanol Vehicle Coalition, Ford no longer require the use of synthetic oil for the lubrication of engines designed to be fuelled with E85. Other car manufacturers like Chrysler may still require special oil for their FFVs (National Ethanol Vehicle Coalition, 2004).

Professor Mathur (Delphi) has reported that he has completed a three-year trial on the road using approximately one hundred government vehicles. He claims that there has not been any problem related to aspects such as storing the fuel, fuelling the vehicles and other issues (Mathur, 2004). One interesting observation is that analyses of samples of lubricating oils have detected no differences in comparisons of the use of ethanol blended fuel and neat gasoline.

A question to consider is whether (and if so to what extent) components in the lubrication oil like sulphur and other chemicals will react with acidic combustion products. The Alliance of Automobile Manufacturers (AAM) and the Association of International Automobile Manufacturers (AIAM) have proposed that additional data on "fuel sulphur effects at near-zero" levels of sulphur should be compiled. They also recommended that data should be gathered on the effects of fuel oxygenates to provide a knowledge base for the California Air Resource Board (CARB) (AAM/AIAM, 1999).

In a Vehicle Buyer's Guide for Consumers published by the US DOE the owners of FFVs are advised to check their service manuals to ensure that the right fuel oils are used (US Department of Energy, 2002). Two of their recommendations for a FFV when using ethanol gasoline blends are:

- "Special engine lubricants may be required when fuelling with ethanol. If you are driving a (FFV), check the owner's manual or consult with the vehicle manufacturer to be sure that you are using the right engine oil.
- When ordering replacement parts for an FFV make sure to let the dealer know you are fuelling with ethanol".

No such recommendations from the US DOE concerning low ethanol-gasoline blends, i.e. those with 10 % or less of ethanol, have been found. _

3.5. *Impact on Service and Maintenance*

A marked lack of wide-ranging, extensive studies of ethanol-gasoline blends with 10 to 30 % ethanol contents was found in the literature search, although blends with up to 25 vol% ethanol in gasoline have been used in Brazil for many years. This is espeally tru for studies of later years models of vehicles. Exceptions are the investigations carried out in Australia referred to in sections 2.7 and 7.1.

Additional service and maintenance instructions to be followed by the service personal and car owners have not been (and are still not) generally issued for FFVs. However, according to the National Renewable Energy Laboratory (NREL) car manufacturers have agreed to apply the same warranties for FFVs as those of vehicles being run on neat gasoline, and the maintenance practises of dealers are very similar for these two types of vehicles. It has also been noted by Ford in literature concerning their Ford Taurus that no special service instructions are needed.

- "FFVs have been used in private and government fleets for years. The technology is proven, and the knowledge base about them is strong. Manufacturers stand behind them with standard warranties equal to those of gasoline vehicles. Dealer maintenance practices for FFVs are very similar to those followed for gasoline vehicles" (NREL, 2003).
- In the information given by Ford Motor Company concerning their FFVs there are: "no special service or maintenance issues with the Taurus Flexible Fuel Vehicle" (Ford Motor Company, 2003).

For vehicles using up to 10 % ethanol in gasoline there does not generally seem to be any need for special service instructions, and for vehicles available on the US market the use of blends with up to 10 % alcohol has been accepted by the car manufacturers. This benefit has been noted by many authors, including Launder (2001) from Michigan State University in a study of the development of ethanol blends in gasoline in the USA from 1970 onwards. As early as 1980 Chrysler, Ford, and General Motors stated that a blend of 10 % ethanol in gasoline would be covered by their warranties for their cars on the US market. By 1995, the same year that Ford started production of FFVs, almost all US car manufacturers were recommending the use of 10 % ethanol in gasoline according to Launder.

3.6. Compatibility and Wear

Studies on engine wear have shown that there is only a slight risk that the use of blends with low alcohol contents will result in increased wear. According to the Canadian Renewable Fuel Association (CRFA) all automobiles sold in North America (the USA and Canada) are "designed with full warranty protection even when they are operated on ethanol-blended gasoline" (Canadian Renewable Fuel Association, 2004). This is consistent with the view of the Australian Consumers Association (ACA) to its members, as stated in the following quotation, "Most of the manufacturers say gasoline containing more than 10 % ethanol can damage car engines, and their new car warranties won't cover such damages" (Australian Consumers Association, 2003).

According to the CRFA's website this warranty is valid for ethanol concentrations up to 10 % and no engine modification is needed (www.greenfuels.org/ethanolterms.html).The CRFA also says that a higher engine compression ratio is advisable for ethanol-gasoline blends above 10 %, but then the warranty may not be valid since increasing the compression ratio may damage the engine. Many car manufacturers in Europe and Japan sell vehicles in North America, and thus the assumption of the authors of the present report is that the design of vehicles on the European market, including Sweden, may allow use of ethanol-gasoline blends with at least 10 % alcohol.

The most serious reported risk associated with blending an alcohol, especially methanol, in gasoline is the potential formation of water vapour and formic acid during low temperature combustion (US Department of Energy, 1991). The proposed solutions of the problem are to use "acid neutralizers in lubrication oils", "surface treatment of engine parts" and more "frequent replacement of lubrication oil or higher quality synthetic oils or a redesign of conventional engine lubrication oils". In the report by the US DOE the following materials are listed as subject to degradation due to high concentrations of alcohols since ethanol may not be compatible with them:

- Lubricating oils.
- Terne steel (in gas tanks).

- Cylinder walls, fuel pumps, carburettors.
- Polymers, elastomers, rubbers, plastics (hoses).
- Polymethane.
- Cork gasket material.
- Leather.
- Polyester bonded fiberglass laminates.

Hsieh et al. (2002) highlight the further potential problem, which may especially apply to older cars, that alcohol tends to react with rubber and they advise that modern cars should be designed to be compatible with the use of alcohol blended gasoline. Many authors of papers dealing with alcohol fuels claim that most problems associated with the use of alcohol, especially methanol, as a fuel for vehicles have occurred in older cars.

According to Hammel-Smith and his colleagues at the NREL, the physico-chemical characteristics of alcohol are different from those of gasoline, which may affect various components, especially in the fuel system (Hammel-Smith et al., 2002). A possible solution could be to use a special corrosion-inhibiting additive. The cited paper also discusses findings reported by other authors. The Oak Ridge National Laboratory has, for example, reported that use of 15 % ethanol-gasoline blends appears to be incompatible with parts of the fuel system according to tests carried out by the Technical Research Centre (VTT) in Finland. Eight out of ten carburetted cars tested showed more or similar wear when compared with gasoline fuelled vehicles. Unfortunately, no information about the two other vehicles appears to be provided in the cited paper.

It was also noted by the Oak Ridge National Laboratory that "Du Pont had found that highly fluorinated fluorohydrocarbons provided the best resistance to either highly aromatic gasoline or to ethanol". Hammel-Smith et al. (2002) have reported, following material tests extending over many years, that these or similar materials may be used in modern vehicle systems. In the report by Hammel-Smith et al. it is also said that "few, if any incidents have been reported on 10% blends associated with 'cylinder wall wash'."

In the investigation by Minnesota State University (referred to above) the use of a 30 % ethanol-gasoline blend did not cause more than normal wear to the engines (Bonnema et al., 2004).

Joseph Jr., representing the Brazilian Automobile Manufacturers Association, has presented a study entitled "Vehicular Ethanol Fuel", describing experience with the use of ethanol-gasoline blends – both anhydrous (99.3 %w) and hydrous (93.2 %w) – in cars in Brazil (Joseph Jr., 1998). One aspect discussed was the effects of ethanol blended gasoline relative to neat gasoline. Brazilian experience suggested that the relative compatibility of the blends with plastic materials was "good" and their tendency to cause the formation of gum deposits was "low". Another conclusion was that a 22 % ethanol blend is more corrosive towards metals than gasoline. On the other hand it was felt that gasoline was as corrosive towards copper strips as a 10 % ethanol gasoline blend. The conclusion of the Joseph Junior presentation is that use of a 10 % ethanol-gasoline blend had no apparent detrimental effect on vehicle performance.

In its Industry Guidelines, Specifications, and Procedures the FRA states that o-rings and seals used in meters for neat ethanol should be "designed to withstand ethanol". On the other hand it states that no accelerated wear has been seen in gasoline meters which are used for ethanol-gasoline blends (Renewable Fuels Association, 2002). However, it also advises that the meters should be recalibrated "10-14 days" after switching to the distribution of ethanol blended gasoline, as noted in section 2.3.

The Guidebook from the US DOE mentioned above provides information on solutions to problems related (*inter alia*) to fuel sampling, one of which may be to check the fuel facilities since their materials may be incompatible with the use of ethanol. There are indications that one potential problem is excessive wear of the nozzles and hoses etc. in the equipment used (US Department of Energy, 2001).

For blends with low ethanol contents (max. 10 %) there has been shown to be no difference between using them and neat gasoline. The engine wear that occurs when using a 10 % ethanol-gasoline blend was studied by Apache Research Ltd in Australia, who found that "there is no additional or unusual wear to that normally expected", and that there was no increase in wear or reduction of TBN (total base number) compared to corresponding parameters when using neat gasoline (Apace Research Ltd, 1998).

There seems to have been an ongoing agreement between the Australian Institute of Petroleum, the Federal Chamber of Automotive Industries and the Australian Automobile Association that a 10 % ethanol content in gasoline is acceptable, but not more, because higher ethanol contents will result in "loss of drivability, loss of fuel economy and accelerated wear of engine components and fuel lines". In addition it will have an effect on the warranty provisions for the vehicle (Australian Automobile Association, 2002).

The ethanol production industry has not agreed to the ethanol content of ethanol-gasoline blends being limited to 10 %, and claims that 10 to 20 % ethanol in gasoline has been used in vehicle fleets since 1992. The industry also made an agreement with a university to study the effects of higher blends of ethanol in gasoline (Department of the Environment and Heritage, 2002).

Several vehicle manufacturers have stated that their vehicles can be run on ethanol-gasoline blends with a 10 % ethanol content without any problem. For example, the Nissan Motor Co., Ltd, which noted approvingly, in a paper released in 2005, that it has been stated in "the News" that "the Minister "the Minister of the Energy Ministry together with the Thai Automotive Industry Association and major fuel suppliers such as the Petroleum Authority of Thailand (PTT), Bangchark Petroleum and Shell announced that the use of gasohol in cars is one way to reduce fuel imports and promote the production of gasohol in Thailand" (Nissan, 2005).

In the cited paper Nissan says that two grades of gasoline are used in Thailand, RON 91 and RON 95, and that MTBE has been added to both of them to date. The essential message from Nissan is that the cost of MTBE can be saved by replacing MTBE with ethanol without decreasing the octane number of the fuel when compared with the gasoline used. Furthermore Nissan states that "Nissan gasoline engines that are equipped with the injection system (EGI) can run on gasohol without any ensuing problem" and that "No modification is required to use gasohol, just open the fuel tank lid and fill it up. You can change back to normal gasoline at anytime, no need to wait until the tank is empty".

In a series of papers Chevron has discussed, *inter alia*, issues related to oxygenated fuels and especially ethanol blends in gasoline (Chevron, 2004), in one of which, entitled "Oxygenated Gasoline", it is stated that in "modern" motor vehicles equipped with engine control systems that adjust the air-fuel ratio, oxygenated gasoline will perform well. However, in vehicles with carburettors or systems for fuel injection that do not control the air-fuel ratio, oxygenate in the fuel may result in a too lean air-fuel mixture". In addition, the volumetric fuel consumption will increase by 2 to 3 percent, on average, according to Chevron when oxygenated gasoline is used. As early as 1978 gasoline containing 10 % ethanol was being marketed in Nebraska, USA.

In California the use of MTBE and other ethers has been banned since 2004, and other states are considering similar bans (Chevron, 2002a). Considering all the available information, from other sources as well as Chevron, it seems likely that ethanol will soon be the only oxygenate that can be used in the USA to satisfy federal requirements for oxygen in gasoline.

In the complete report (Chevron, 2002a) Chevron discusses the implications of the observation that "Methanol is Not Ethanol" in that they have different physico-chemical characteristics. According to Chevron:

- Blends of gasoline with methanol are more corrosive towards metals and cause more rapid deterioration of elastomers in the fuel system.
- Methanol-gasoline blends are not authorized by many manuals for vehicle owners.
- The vapour pressure of a methanol-gasoline blend is significantly higher than that of a corresponding ethanol-gasoline blend.
- Methanol is toxic.

In addition, the following performance-related issues have been highlighted by Chevron:

- Compared to neat gasoline, ethanol/gasoline blends need more heat to evaporate, which can reduce drivability.
- Blending ethanol in conventional gasoline, if it is not adjusted for such blending may result in a fuel with too high volatility (in this context the alcohol's previously mentioned effect on the VL = 20 temperature is relevant).
- Since ethanol increases the volatility of the fuel, adding it has not been a viable option for summer reformulated gasoline.
- Ethanol blended gasoline is not to be mixed with neat gasoline that has not been adjusted for such blending, since the resulting commingling will result in the RVP of the fuel in the tank exceeding standard limits.
- Conventional gasoline can dissolve up to 150 ppm water at 21 °C, depending on its aromatics content. An ethanol-gasoline blend with 10 % ethanol can dissolve up to 6000 to 7000 ppm water at 21 °C. Phase separation may occur if ethanol blended gasoline is transported in pipelines.
- Some metal components in the engine fuel system will rust or corrode if water or acidic compounds are present in the fuel system. According to Chevron "additional water dissolved in oxygenated gasolines does not cause rusting or corrosion, but water from the phase separation of gasoline oxygenated with ethanol will, given time".

3.7. Impact of Vapour Lock

Vapour lock is caused by the fuel flow to the engine being reduced as a result of vapour formation, typically caused by high temperatures, while the vehicle is being driven. Vapour lock can also make it impossible to start the engine. This problem may be exacerbated in carburettor-equipped vehicles.

Vapour lock is linked to the vapour pressure of the fuel, which is a measure of the front end volatility* of the fuel. Fuels with extremely high vapour pressure may cause drivability and hot start problems as a result of vapour lock. Since the addition of an alcohol to gasoline will

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* Front-end volatility: A term applied to the volatility of the lower boiling-point fractions of gasoline.

increase the volatility of the fuel, there is a risk that it will also cause vapour lock to occur in hot weather or at high altitudes.

A paper published by Chevron recommends that fuels should not exceed specified Vapour Lock Index (VLI) values in order to avoid problems such as vapour lock and hot fuel. The following formula has been developed for calculating the VLI based on the vapour pressure (in kPa) and percent evaporated fuel at 70 °C: $VLI=10(VP)+7(E70)$. The normal range for the VLI, according to Chevron, is 800 to 1250, and protection from vapour-linked problems is greatest at the lower end of the range (Chevron, 2002).

4. AIR QUALITY AND HEALTH EFFECTS

Air quality can be considered at three levels: global, regional and local. From a global perspective, the most important greenhouse gases are nitrous oxide, carbon dioxide and methane, all of which affect the global climate. Increased use of bio-based fuels, especially as blending components in gasoline, is expected to decrease the net production of carbon dioxide from fossil fuels in vehicles, which is an important issue for sustainable development. By introducing bio based fuels the net production of fossil carbon dioxide from vehicles is expected to decrease with increased amounts of bio based blending components in gasoline which is an important issue for sustainable developments.

Colón et al. (2001) have compared the urban air levels of organic compounds in Sao Paulo, Brazil, and the Los Angeles basin, USA. In Sao Paulo it is estimated that ethanol or ethanol-gasoline fuel blends account for approximately 40% of the total fuel used, but the corresponding level in the Los Angeles basin is much lower, hence the urban air in Sao Paulo is much more strongly affected by the use of ethanol as motor fuel.. It was found that the ambient air levels of volatile organic compounds measured in Sao Paulo were substantially higher than those in Los Angeles. For instance, mean concentrations of mono ring aromatics, volatile aldehydes and "simple" alcohols (mainly ethanol) were 2 - 3, 5 - 10 and 10 - 100 times higher, respectively. Alkanes (C_4-C_{11}, n-alkanes) were slightly increased in Sao Paulo. The ambient levels of organic compounds in the Los Angeles basin used by Colón in the comparisons were based on measurements made by the US EPA in the year 1997 (Lonneman, 1998). A study regarding carbonyls in urban air, collected in Rio de Janeiro, Brazil, revealed that of the 61 carbonyl compounds measured the most abundant were formaldehyde and acetaldehyde, with mean concentrations of 10.8 ± 4.1 and 10.4 ± 4.6 ug/m^3, respectively (Grosjean et al., 2002).

Maclean and Lave (2000) have investigated air quality trade-offs from automobiles fuelled by alternative fuels. They state that comparisons can be misleading if the vehicles used are dissimilar. One of the fuels considered was E85 i.e. 85% ethanol and 15% gasoline. Aakko and Nylund (2003) investigated an FFV running on E85 and found that when the temperature was lowered from 23 °C to −7 °C formaldehyde and acetaldehyde emissions increased (the latter approximately four-fold; from 4 to 15 mg/km driven).

Exhausts from mobile sources such as motor vehicles are chemically very complex. The chemical compounds emitted range from gaseous, liquids to particles (solids) and may also be distributed between particles and the gas phase depending on the physical properties of the compounds. Particle emissions consist mainly of carbon particles onto which a variety of compounds are adsorbed. Up to 10-40 % by weight of the particles can be extracted from the carbon matrix with organic solvents (National Research Council, 1982). Such an extract is often referred to as the soluble organic fraction (SOF).

Several factors affect the chemical composition of the exhaust emissions, including the fuel, fuel quality, engine lubricating oil, engine wear, exhaust after treatment, driving conditions and ambient temperatures. Ambient temperature driving conditions, which of course depend on seasonal variations, can have a major impact on emissions, especially for Otto engines, both with and without three-way catalysts (Almèn et al., 1997) at low ambient temperatures from +20 °C down to −20 °C or lower. Investigations of light duty diesel engines have indicated that they are relatively unaffected by the ambient temperature compared to investigated Otto engines. This could be due to the differences in the combustion mechanisms of Diesel and Otto engines. Aakko and Nylund (2003) investigated exhaust emissions from an FFV running on E85 at temperatures of +20, 0 and −7 °C, and concluded that the emissions of CO, HC and total particles increased as the temperature was lowered while NOx emissions were only slightly increased.

Another important factor affecting the chemical composition of exhaust emissions generated in the combustion process in an engine is the service and maintenance history of the vehicle/engine. Extremely high levels of both regulated and unregulated emissions have been detected in exhaust emissions from gasoline fuelled vehicles that have been poorly serviced and maintained, i.e. incorrectly functioning engines or so-called high emitters (Sjödin et al., 2000). High emitters should be mended or eliminated from the car fleet in general.

Armstrong (1995) has evaluated ethanol as an individual compound and states that it is readily degraded in the environment, so human exposure to it is anticipated to be very low. Furthermore, abundant information is available on the metabolism of ingested ethanol, which strongly suggests that environmental exposure to ethanol will have no adverse health impact on humans. Average ambient levels of ethanol in Porto Alegre, Brazil, where 17% of the vehicles run on ethanol have been found to be 12 ppb. Animal studies have found that the Lowest Effect Level (the lowest level to give a detectable response) of ethanol is 45 ppm, which is approximately 4000 times higher. The dose for a person living in Puerto Alegre might be about 0.5 mg ethanol, which is a negligible dose.

In section 5.3 a selection of exhaust constituents that may have adverse effects on the environment or health of animals and humans is listed and discussed.

5. EMISSIONS

In an investigation by the Swedish government entitled "Alternativbränsleutredningen*" (SOU, 1996) it was proposed that a thorough chemical characterization of exhaust emissions (regulated and unregulated exhaust constituents) of gasoline blended with alcohols should be carried out. Furthermore, it was suggested that bio assays, such as mutagenicity tests, TCDD-receptor affinity tests and neurotoxicity tests, should be included in the risk evaluation. The risk criterion was that the modified fuel alcohol/gasoline blend should not have any greater potential environmental and health impact than a baseline gasoline fuel. However, an updated set of compounds and classes of compounds that should be considered is discussed below.

5.1. Regulated exhaust emissions

Emissions that are regulated by law (Lagen, 2001) are carbon monoxide (CO), unburned fuel hydrocarbons (HC), nitrogen oxides (NOx) and, for diesel cars, particles. The methods used to determine regulated pollutants have been developed for application to conventional fossil based gasoline and diesel fuels. These methods are: chemiluminescense detection for NOx, nondispersive infrared detection (NDIR) for CO, gravimetric analysis for particulates and flame ionization detection (FID) for HC. The chemical constituents of HC are, by definition, hydrocarbons which consist solely of carbon and hydrogen atoms. However, the chemical compounds emitted include compounds other than pure hydrocarbons (see below) in relative abundances that vary depending on the fuel used, so the "HC" signal from the FID tends to be underestimated. This is because the hydrocarbons and partially oxygenated compounds have different response factors, as widely reported in the scientific literature (Table 5.1). Consequently, to make a valid comparison of HC emissions from gasoline and ethanol blended gasoline as fuels the comparison must be made compound by compound to avoid over- or under-estimations. This requires the development of a method enabling the separate detection of hydrocarbons and alcohols (at least) in exhaust emissions.

Table 5.1. Sensitivity of the flame ionization detector towards selected compounds relative to that of the hydrocarbon n-heptane (C_7H_{16}), which is set to 1.00 (Diez, 1967).

Hydrocarbons		**Alcohols**		**Organic acids**	
Methane	0.97	Methanol	0.23	Formic acid	0.01
Ethane	0.97	Ethanol	0.46	Acetic acid	0.24

Emission measurements must be carried out as part of the type approval of the vehicle according to relevant legislation, for example the European regulations (current EU Directive 70/220/EEG with amendments). There is also a need for emission testing to generate emission factors for use in emission inventories and air quality studies. Characterisation of emissions from vehicles is also essential for research purposes. Emission tests are commonly carried out according to standard procedures to enable data generated at different laboratories or during different projects to be compared. There may also be a need to generate emission factors for local traffic situations,

* Investigation of alternative fuels.

in which case specific driving patterns (driving cycles) may have to be followed when testing the vehicles, depending on the regulations in force.

5.2. Theoretical Discussion about HC Emissions

From a strictly chemical perspective, hydrocarbons consist solely of the elements carbon and hydrogen. When using gasoline as fuel in an Otto engine, the unburned fuel hydrocarbons (HC) in the exhaust consist mainly of unburned gasoline which itself largely consists of hydrocarbons. However, when using gasoline/ethanol blends as fuel the uncombusted fuel constituents include both unburned gasoline (which consists mainly of hydrocarbons as noted) and uncombusted ethanol. Thus, the HC emissions measured in the diluted exhaust consist of both hydrocarbons and ethanol (alcohol). From a legal perspective, HC emissions are regulated by law (see section 5.1), but not ethanol emissions. This means that reported HC emissions from vehicles fuelled with alcohol/gasoline blends are overestimated, due to the contribution of the alcohol* contents in the exhaust emitted from the vehicle, and the larger the alcohol contents present in the exhaust, the greater the error in estimated HC emissions.

Assume, for example, that a vehicle is run on gasoline and has HC emissions of 0.15 mg/km (i.e. uncombusted fuel hydrocarbons), and that the same vehicle is run on a gasoline blend and the measured "HC" emissions are also 0.15 mg/km (consisting of both uncombusted fuel hydrocarbons and uncombusted ethanol) in comparative tests.

The standard analytical method used for determining hydrocarbons in motor vehicle exhaust is to use a Flame Ionization Detector (FID), which can be regarded as a "carbon counter". The relative sensitivity of an FID for each of the hydrocarbons methane, ethane, propane and pentane is approximately 1 (Dietz, 1967). The corresponding value for ethanol is 0.46. Using these relative sensitivity factors, and assuming that only hydrocarbons are present in the exhaust the HC emission factor will be 0.15 mg/km, but if only (100%) ethanol is present in the exhaust the ethanol emission factor from the vehicle is in reality 0.33 mg/km However, if only ethanol is present in the exhaust the "HC" emission measured is still 0.15 mg/km but should be practically zero as no hydrocarbon is present in the exhaust.

The above discussion highlights the need to distinguish between HC and alcohol contents in vehicle exhaust, especially when alcohol gasoline blends are used as fuel. An updated method needs to be developed for HC measurements from a legal perspective. This also means that a standardized method needs to be developed.

5.3. Unregulated Exhaust Emissions

It is well known that the addition of alcohols to gasoline fuel affects the unregulated exhaust emission constituents (Egebäck and Bertilsson, 1983). For instance, addition of methanol to gasoline increases the exhaust emissions of unburned methanol, formaldehyde, and methyl

* Other compounds, such as alcohols/aldehydes, also contribute to the signal from the FID.

nitrite. Corresponding additions of ethanol to gasoline increase the exhaust emissions of unburned methanol, ethanol, formaldehyde, acetaldehyde, methyl nitrite and ethyl nitrite.

The US EPA has estimated that more than 20,000 individual chemical compounds are emitted from diesel fuelled vehicles (US EPA, 1990), approximately 500 of which have been positively/tentatively identified in the scientific literature. This means that more than 97 % of the estimated compounds emitted from diesel vehicles are unknown (as are, therefore, their health effects). However, a selection of unregulated exhaust constituents is considered below that are considered to be important and to have potential health effects on animals and humans, and thus should be monitored and reduced in exhaust emissions from automotive sources. Greenhouse gases and smog-forming compounds are also considered. The list of such compounds is expected to be updated and modified according to future findings.

Alcohols

When alcohols are used as blending components in gasoline, uncombusted alcohols from the fuel are emitted in the exhaust in various amounts. These uncombusted alcohols in the exhaust emissions should be measured since there is a risk that the "HC" signal from the FID will be overestimated, leading to estimates of HC emissions from alcohol blended gasoline fuels being higher than they really are (see Regulated exhaust emissions regarding HC section 5.1).

Aldehydes

Aldehydes are known to be irritants, they may induce allergic reactions and formaldehyde is considered to be a carcinogen (CARB, 1989). Aldehydes of special interest are formaldehyde and acetaldehyde. Using ethanol as a blending component in gasoline results in increased emissions of both formaldehyde and acetaldehyde (Egebäck and Bertilsson, 1983). According to Aakko and Nylund (Aakko and Nylund, 2003) significant increases in aldehyde emissions occur at relatively low ambient temperatures (-7 °C). The effect is expected to be even greater at lower ambient temperatures than -7 °C, especially for ethanol-gasoline blended fuels.

Alkenes

Alkenes such as ethene, propene and 1,3-butadiene can be potentially metabolized by endogenous enzymes to reactive metabolites, which have the potential to initiate cancer. For instance, the compound 1,3-butadiene is metabolized to ethylene oxide in both animals and humans (Törnqvist et al., 1988; 1991). According to Schuetzle et al. (1994) significant sources of 1,3-butadiene are the olefins in the fuel. By blending gasoline with ethanol the "fuel olefin" content decreases, suggesting that emissions of alkenes are reduced when it is used rather than neat gasoline. However, this hypothesis needs to be experimentally confirmed.

Alkyl nitrites

Methyl and ethyl nitrite are mutagenic (Törnqvist et al., 1983; Wild et al., 1983), hence they are potential carcinogens. Alkyl nitrites are formed from uncombusted alcohol reacting with nitrogen oxides (NOx) in exhaust plumes. From vehicles fuelled with methanol/gasoline blends and methanol/diesel blends methyl nitrite is formed (Johnsson and Bertilsson, 1982). Both methyl and ethyl nitrite are formed in exhaust plumes from vehicles fuelled with ethanol-gasoline blends (Egebäck and Bertilsson, 1983).

Monoaromatics

Monoaromatic compounds emitted from vehicles include benzene, toluene, ethyl benzene and xylene, which are often collectively called BTEX. According to the California Air Resources Board (CARB, 1998) benzene is a known human carcinogen and may cause leukaemia through occupational exposure (Törnqvist and Ehrenberg, 1994). A source of BTEX emissions from vehicles is the BTEX content of the fuel used, emitted in the uncombusted fuel constituents. However, BTEX can also be pyrosynthesised in the combustion process from the fuel or lubricating oil constituents.

Particulate emissions

Particlulate emissions are measured on a weight basis i.e. through gravimetric determination using a dilution tunnel technique at a diluted exhaust temperature below 52 °C. Exposure to diesel exhausts clearly induces lung tumours in rats. These neoplasms may be caused by the particle fraction of the exhaust (International Agency for Research on Cancer, IARC, 1983; 1989; Camner et al., 1997). Due to the findings that TiO_2 and carbon black particles, with no genotoxic compounds adsorbed on them (i.e. "clean" particles) can also give rise to lung cancers in rats (Pott, 1991; Pott and Heinrich, 1990; Heinrich et al., 1993) interest in particles *per se* has increased. Important particle parameters in general are their size, number, surface area and chemical composition. Studies by Heinrich et al. (1995) indicate that particle size is a very important parameter. The Institute of Environmental Medicine (Karolinska Institute, Sweden) has published a report which concludes that it is not currently possible to tell if a non-specific particle factor or a direct genotoxic effect of material adsorbed on the particles is responsible for causing lung cancer (Camner et al., 1997). Therefore, the particles emitted should be chemically analysed with respect to both their size and numbers.

Peroxyacetyl nitrate

In a study by Gaffney et al. (1997) field measurements taken in Albuquerque, New Mexico, were used to compare atmospheric levels of peroxyacetyl nitrate (PAN) associated with the use of different fuels. Levels were measured before and after introduction of a 10% ethanol gasoline fuel blend (>99%) and the cited authors detected increased levels of PAN and aldehydes during the wintertime. A study which is more valid during summertime conditions in Porto Alegre, Brazil, (Grosjean et al., 2002) indicates that aromatics and alkenes have a major role, and acetaldehyde and ethanol minor roles, as precursors to PAN in urban air – in contrast to a report prepared by the Orbital Engine Company (2002) for Environment Australia, which states that acetaldehyde is particularly important since it reacts with NOx, forming PAN in the atmospheric photochemical system. In the report it is stated that acetaldehyde emissions increase as the ethanol content in the blended gasoline fuel increases. This conclusion is supported by the results of several other investigations.

Polycyclic Aromatic Compounds

Polycyclic Aromatic Compounds (PACs) are a numerous group of mutagenic carcinogenic compounds, of which a subgroup (Polycyclic Aromatic Hydrocarbons or PAHs), consists of mutagenic carcinogenic hydrocarbons (IARC, 1983; 1989). Each PAH has a relatively large number of hydrocarbons with two or more condensed aromatic rings. However, in Sweden are the PAHs phenanthrene, fluoranthene, pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenz(a,h)anthracene, dibenzo(a,l)pyrene, methyl anthracenes/phenanthrenes, retene and benzo(ghi)perylene recommended by the Swedish

Environmental Protection Agency (SEPA) for air monitoring programs in 1999, however published in 2002 (Boström et al., 2002). Recommended guideline value concentrations in ambient air are set to 0.1 ng/m^3 for benzo(a)pyrene (B(a)P) and for fluoranthene 2 ng/m^3 in Sweden (Boström et al., 2002). So far B(a)P is the only PAH whose concentration in ambient air will be regulated by European Commission and the limit value will most probably be set to 1 ng/m^3. However, at present the European Parliament has not made a final decision about the limit value according to Kyrklund (Kyrklund, 2004).

Nitrogen dioxide

Nitrogen oxides (NO and NO_2) are formed by the oxidation of nitrogen from the air in the combustion process. An important parameter for the formation of nitrogen oxides is the combustion temperature i.e. increased combustion temperature results in increased nitrogen oxide emissions. Nitrogen dioxide (NO_2) is a compound that plays a role in respiratory diseases, especially those of asthmatics and children (Nitschke, 1999). It should be noted that nitrogen oxides (NOx) are regulated pollutants that are determined jointly, as the sum of NO and NO_2 contents rather than as individual components.

Greenhouse gases

Greenhouse gases of most interest are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), all of which interact with the radiative energy fluxes in the atmosphere, thereby increasing the average temperature of the earth. In Table 5.2 the Global Warming Potential (GWP) for selected greenhouse gases is shown. The GWP indicates the relative contribution of a molecule of a greenhouse gas compared to a molecule of carbon dioxide, for which GWP is set to one. According to Rodhe (2005), the background concentration in the atmosphere of carbon dioxide is 375 ppmv (yearly variation, +/- 2 ppmv), while the background concentrations of methane and dinitrogen oxide (nitrous oxide) are 1.75 ppmv and 0.315 ppmv, respectively. By multiplying the concentration of a greenhouse gas and its respective GWP, its relative contribution to the global warming effect can be estimated. Clearly, the most important greenhouse gas is carbon dioxide, due to its relative abundance in the atmosphere.

Table 5.2. Global Warming Potential (GWP) and the relative contribution to the global warming effect (RCGWE) of selected compounds.

Compound	GWP	Concentration ppmv	GWP x ppm	% RCGWE
Carbon dioxide, CO_2	1	375	375	74
Methane, CH_4	23	1.75	40.3	7.9
Dinitrogen oxide, N_2O	296	0.315	93.2	18

Quinones

A recent publication by Xia (Xia et al., 2004) shows that a quinone-enriched polar fraction from a diesel particulate extract was more potent than PAH with respect to toxic effects in RAW 264.7 cells macrophage-like cells derived from tumours induced in male BALB/c mice by the Abelson murine leukemia virus. Quinones are a group of organic compounds that consist of diketones (carbonyls) which contain oxygen and are present in both diesel particles (Schuetzle et al., 1981) and ambient air (Cho et al., 2004). Aromatic quinones have previously been identified and measured in gasoline particulate exhaust extracts (Schuetzle et al., 1981; Alsberg et al., 1985). The origin of the aromatic quinones is not fully understood if it is related to the gasoline fuel as uncombusted quinones (initially in the fuel) or if they are formed in the combustion process.. It is well known that fuel properties affect the chemical composition of the exhaust emitted from engines. For instance, adding ethanol to gasoline increases the emission of aldehydes (carbonyls). It is possible that increasing the ethanol content of gasoline-ethanol blends causes similar increases in quinone emissions, but there are no empirical data related to this issue as yet.

5.4. Characterisation of Exhaust Emissions

In a relatively recent publication He et al. (2003) present a study of exhaust emission characteristics from an engine with an electronic fuel injection (EFI) system with and without a three-way catalyst (TWC) system. The engine was run on neat gasoline, and both 10 % ethanol- (E10) and 30 % ethanol- (E30) gasoline blends (see section 1.2, Table 1.1). The engine out emissions at idle speed using E30 as fuel it was observed that HC, CO and NOx emissions was reduced and ethanol and acetaldehyde emissions was increased. It was also observed that the TWC system reduced acetaldehyde emissions, but had a low conversion efficiency for ethanol.

In Table 5.3 mean emission factors are shown from three TWC-equipped cars running on 3, 6 and 10 vol. % ethanol-gasoline blends (Schifter et al., 2001). It is difficult to interpret or to draw firm conclusions from the data in the table, as they are mean values from three cars. However, NOx, benzene and acetaldehyde emissions increased with increasing ethanol contents, while CO and formaldehyde emissions and the ozone formation factor (g O_3/g Non Methane Organic Gases, NMOG) decreased.

Table 5.3. Mean emission factors from three TWC-equipped cars running on 3, 6 and 10 vol. % ethanol gasoline blends (Schifter et al., 2001).

Emission	**3 % Ethanol**	**6 % Ethanol**	**10 % Ethanol**	**Ethanol effect**
CO, g/km	3.11	2.89	2.97	-
HC, g/km	0.23	0.21	0.22	0
NOx, g/km	0.42	0.42	0.48	+
g O_3/g NMOG	3.12	3.09	3.08	-
Benzene, mg/km	7.22	7.38	8.11	+
Butadiene, mg/km	0.83	0.77	0.83	+/-
Formaldehyde, mg/km	1.32	0.78	1.01	-
Acetaldehyde, mg/km	1.12	1.25	1.62	+

In Table 5.4 the mean fuel economy and mean evaporative emissions from the three TWC-equipped cars running on 3, 6 and 10 % ethanol gasoline blends are shown.

Table 5.4. Mean fuel economy and mean evaporative (Evap) emissions from three TWC-equipped cars running on 3, 6 and 10 % ethanol-gasoline blends (Schifter et al., 2001).

	3 vol % Ethanol	**6 vol % Ethanol**	**10 vol % Ethanol**	**Ethanol effect**
Fuel consumption l/10 km	0.87	0.85	0.87	+/-
Evap. diurnal, g/test	4.14	3.77	4.60	+/-
Evap. hot-soak, g/test	0.46	0.44	0.68	+

Regarding emissions of benzene, toluene, ethyl benzene and xylene (BTEX) a general conclusion is that as the ethanol content of the blended fuel increases the BTEX emissions are reduced (Orbital Engine Company, 2002) by the dilution of the base gasoline.

In a study carried out in Australia (Orbital Engine Company, 2004) the unregulated emissions such as BTEX and aldehydes were measured. The emission measurements were made using fuels comprising of 20% ethanol (E20) in gasoline and neat gasoline. Furthermore, the vehicle emissions were determined at both 6400 and 80000 km odometer readings. In Figure 5.1 shows average benzene emissions from five tested cars. The Holden car decreases its benzene emissions with increased driving distance. The benzene emission is lower when the E20 fuel is used as fuel and the emission is reduced at increased driving distance. Comparative benzene emissions from the Hyundai car is that benzene emissions increase as the driving distance increases which is valid for both fuels tested. Furthermore, the Subaru car has larger benzene emissions from the E20 fuel compared to neat gasoline. From the Figure 5.1 it can be concluded that there is a relatively large variation in benzene emissions due to fuel and accumulated driving distance and vehicle tested. Because of this, it is difficult to make firm conclusions with respect to benzene emissions vehicle dependency.

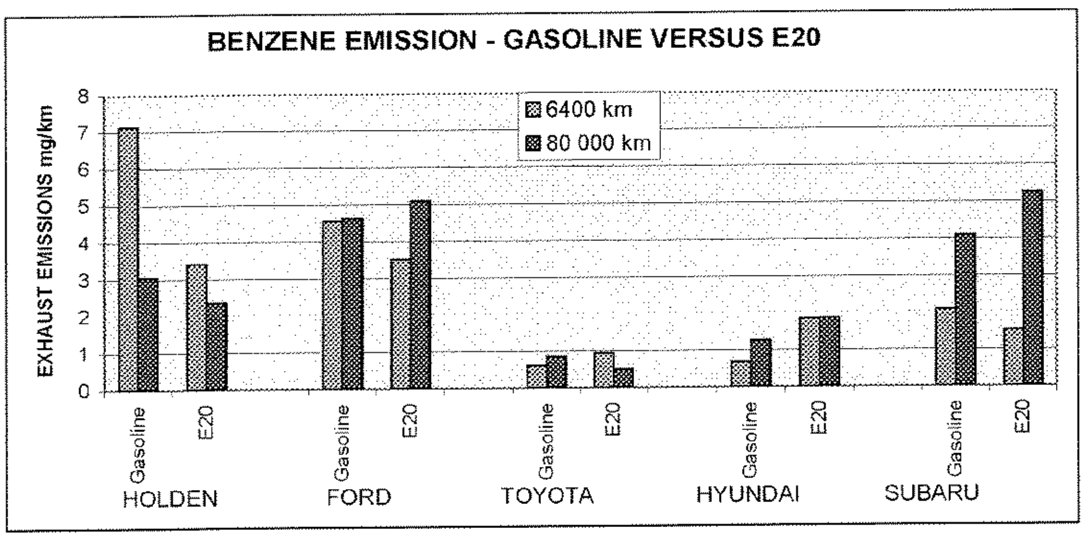

Figure 5.1. Benzene emissions (mg/km) gasoline versus E20.

Figure 5.2 shows average acetaldehyde emissions from all vehicles tested. From the figure it can be seen that increased accumulate driving distance results in an increased acetaldehyde emission, however the Toyota car is excluded. This seems to be fuel independent. From the Figure 5.1 it can be concluded that the there is a relatively large variation in acetaldehyde emissions due to fuel and accumulated driving distance and vehicle tested. Because of this, it is difficult to make firm conclusions with respect to formaldehyde emissions vehicle dependency.

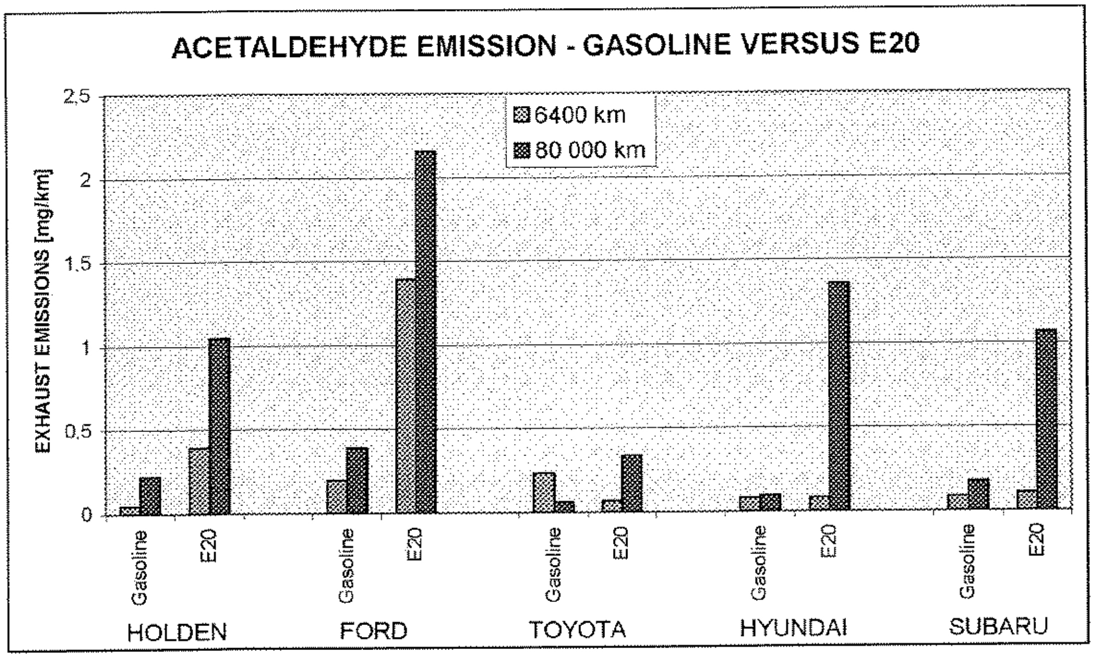

Figure 5.2. Acetaldehyde emissions (mg/km) gasoline versus E20.

Figure 5.3 shows average formaldehyde emissions from all vehicles tested. All of the tested vehicles had increased formaldehyde emissions with respect to increased accumulative driving distance. The relative emissions of formaldehyde are vehicle and fuel dependant.

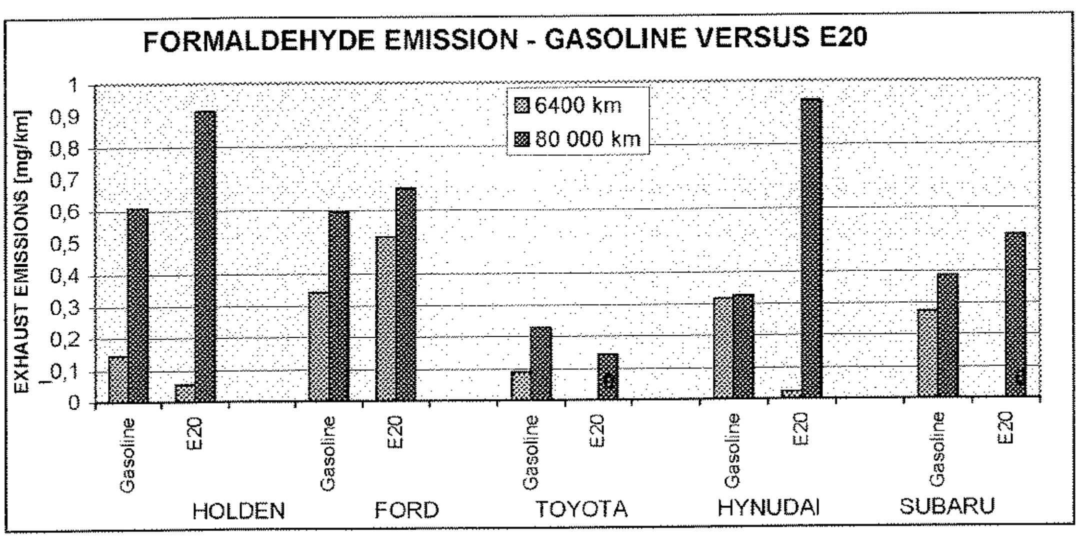

Figure 5.3. Formaldehyde emissions (mg/km) gasoline versus E20.

Summing up, from Figures 5.1 to 5.3 due to accumulative driving distance the function of the catalysts is deteriorating which results in increased emissions of benzene, acetaldehyde and formaldehyde emissions. The gasoline fuel used contains up to 500 ppm sulphur which is extremely large compared to gasoline available on the Swedish market which is expected to have an impact on the exhaust emissions.

6. FUEL ENERGY CONTENT – ENGINE POWER.

Since ethanol has a significantly lower energy value than gasoline its addition may affect the engine's power even though the octane number of ethanol is higher than that of gasoline. Since there has been a lack of standard protocols for measuring the octane numbers RON and MON for ethanol the presented range for them is quite wide: 102 – 130 for RON and 89 – 96 for MON according to Environment Canada. Furthermore, the octane numbers for gasoline vary depending on its composition. The octane numbers presented for ethanol blended gasoline are 90 – 100 for RON and 80- 92 for MON (Prakash, 1998; Environment Canada, 2005).

The engine's power output depends on the energy content per unit volume fuel injected into its combustion chamber. The reduction in energy content per unit volume fuel caused by adding five different percentages of ethanol to a certain blend of gasoline is shown in Figure 6.1.

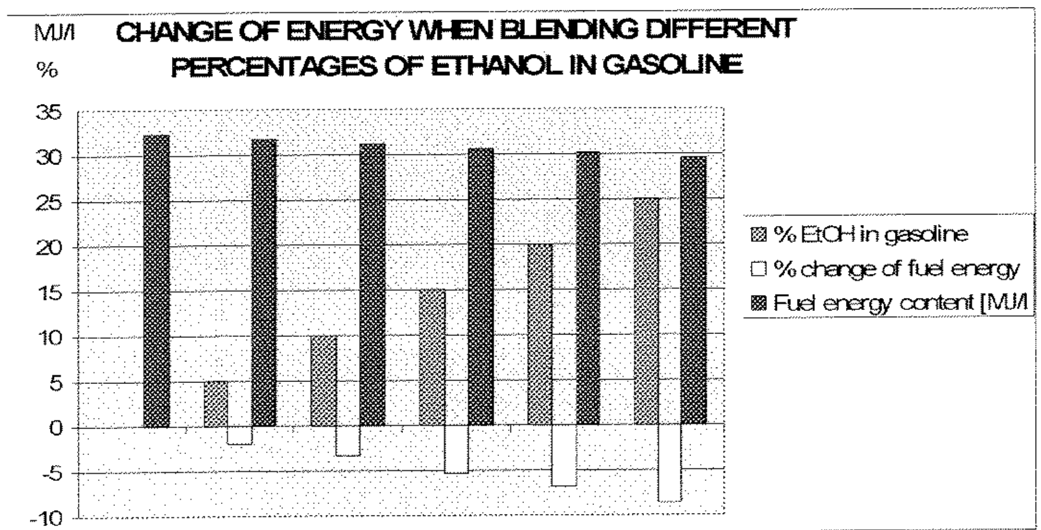

Figure 6.1. The effect of blending ethanol with Swedish Class 1 (MK1) gasoline on the fuel's energy content.

When adding ethanol up to 25 % the energy change may be sufficient for the driver to clearly detect a change in the engine's power* during acceleration of the vehicle. However, vehicles produced today are designed to adjust the air-fuel ratio in order to compensate for changes in the fuel. It is well known that vehicles are equipped with systems for adaptive learning or adaptive memory, and according to information obtained from Web FAQs, "Modern adaptive learning engine management systems control the combustion stoichiometry by monitoring various ambient and engine parameters, including exhaust gas recirculation rates, the air flow sensor, and exhaust oxygen sensor outputs" (Hamilton, 2004).

The conclusion is that an addition of 10 to 15 % ethanol to gasoline will, to a certain degree, increase fuel consumption. However, in the literature study it was not possible to find a

* As the energy content (MJ/l) of ethanol gasoline blends is lower than that of neat gasoline the fuel consumption will most likely increase for the average driver.

definitive percentage for the increase since it depends on a number of factors, of which the design of the fuel system of the vehicle and engine, the percentage of ethanol in the fuel and the driving pattern of the vehicle appear to be most important.

An issue to consider is whether the owner of the vehicle will recognize the increase in fuel consumption that may occur when ethanol is added to gasoline. In a report prepared by the Orbital Engine Company for Environment Australia concerning an investigation into the use of 20 % ethanol in gasoline it is stated that the "increase in fuel consumption ranges from 2.5 % to 7 % depending on the cycle and the vehicle". In the same report Orbital also states that "Increases in fuel consumption of 5% or more are considered to be recognisable to the average driver" (Orbital Engine Company, 2003).

Results presented by Apache Research Ltd. from an investigation of the use of a blend of 10% ethanol in gasoline show that fuel consumption increased by 2.4 % when driving according to the US EPA City cycle and by 2.7 % when driving according to the Highway cycle (Apache Research Ltd, 1998). According to the statements by Orbital this increase in fuel consumption should not be detectable by an average driver.

In a paper from the Transportation Office of Energy Efficiency in Canada it is said that adding 10% ethanol to gasoline (E10) will result in a blend with an energy content equivalent to 97 % of the energy content of the base gasoline. Since this decrease in energy content will be partly compensated by the "improved combustion efficiency" of the ethanol blended fuel, the overall increase in fuel consumption when using E10 will be only 2 %. In comparison, increasing the speed of the vehicle from 100 km/h to 120 km/h will result in a 20 % increase in fuel consumption (Transport Office of Energy Efficiency in Canada, 2004).

7. EVALUATION OF EMISSIONS AND FUEL CONSUMPTION

In a paper released in 1992 the US EPA defined "Clean Fuels" as including "alcohols, electricity, natural gas, and propane" (US EPA, 1992). In the paper the EPA also declare that "Some vehicle fuels, because of physical or chemical properties, create less pollution than do today's gasoline. These fuels are called "clean fuels."

A key issue today is whether newly manufactured gasoline-fuelled vehicles equipped with an efficient emission control system emit more or less harmful substances than vehicles fuelled with any of the fuels mentioned in the paper from the EPA. It can also be questioned whether any automotive fuel used today can be defined as a "clean fuel" since all types of fuels generate pollution when burned in a combustion engine.

Concerning the use of a blend with a certain content of ethanol in gasoline it is quite clear, as already mentioned in this report, that there is a risk that emissions, especially of acetaldehyde, will increase, but those of benzene, toluene, ethylbenzene and xylene (BTEX) may decrease compared with the use of neat gasoline in the same vehicle. Whether (and if so to what degree) these changes will be better or worse overall in terms of the air quality and health has been considered in various studies, especially in the USA/California, and in this report. The most important issue to clarify is whether, and if so to what extent, the regulated emissions will change compared with the use of neat gasoline when switching to the use of a blend of ethanol/gasoline. Hammel-Smith and his colleagues at NREL have indicated that a key aspect concerning vehicle performance and emissions when using a blend of ethanol/gasoline of up to 17 to 24 % is that fuel control is able to compensate for a high oxygen content in the fuel (Hammel-Smith et al., 2002).

One of the conclusions to be drawn is that it is generally not certain that a higher blend of ethanol can be used in all vehicles currently available. Potential barriers in this respect are the age of the vehicles, their technological standards and their control systems. Electronically controlled fuel injection systems have long replaced carburettors and they are more advanced today in that new functions have been incorporated. The use of electronic mapped digital systems makes it possible to control ignition, fuel injection, emissions and automatic transmission in addition to other engine variables. According to the NREL these systems have been important in the evolution of the use of alcohols as automotive fuels (Hammel-Smith et al., 2002).

When considering the performance and emissions from motor vehicles, especially vehicles using blends of ethanol in gasoline, the technological status of the vehicle should be considered. It is accepted that adding an alcohol, i.e. ethanol, in gasoline will enhance the octane rate of the fuel. On the other hand it has been shown in section 6 of this report that blending ethanol in gasoline will decrease the energy content of the fuel, resulting in an increase of the volumetric fuel consumption. In vehicles equipped with advanced engine control systems the ability to exploit the higher octane rating compensates, to a certain degree at least, for the inevitable drop in the energy content of the fuel.

When considering the effect of blending ethanol with gasoline on emissions a factor that must be taken into account is that motor vehicles are sensitive to changes that affect the air/fuel ratio. This is especially true for vehicles equipped with older types of fuel systems, such as carburettors or open loop fuel injection systems. Newer models of vehicles equipped with closed-loop fuel injection systems, especially those with advanced closed-loop fuel injection systems with adaptive learning functions are less sensitive in this respect.

When using alcohol blended gasoline it has been observed that NO_x emissions may increase compared to the use of neat gasoline due to the leaning effect of the alcohol. This effect does not generally occur when using alcohol blended gasoline in newer models of vehicles.

During the survey of reports presenting data and experience related to the use of ethanol blended gasoline some data from emission and fuel consumption measurements have been found. In the following sections these data and experiences are briefly described. When reading the tables and studying the figures it should be noted that presented data on HC emissions include components other than hydrocarbons, as discussed in sections 5.2 and 5.3.

7.1. Evaluation of Emissions in Australia

In Australia a number of investigations and emission tests have been conducted during the last five to seven years in a project initiated by the Department of the Environment and Heritage entitled "Market Barriers" (2004). The project which finally included different parts was performed as an initiative of the Department of the Environment and Heritage project "Market Barriers to the uptake of Bio fuels – Testing Petrol Containing 20 % Ethanol (E20)" (Orbital Engine Company, 2004). The tests carried out included comparative measurements of emissions from engines from engines running on neat gasoline and a blend of 20 % ethanol (E 20) in gasoline in pairs of the following five vehicles.

- Holden Commodore VX.
- Ford Falcon AU-III.
- Toyota Camry Altise.
- Hyundai Accent.
- Subaru Impreza WRX.

Two types of gasoline (AEN* Summer ULP and AEN Perth ULP; designated ULP and PULP, respectively) were used as base gasolines for blending with ethanol. The difference between the two types of gasoline, according to Orbital, is as follows: "In summary, there are some small but quantifiable differences to be taken into account when comparing trends over the accumulated mileage and across some of the vehicle fleet using the ULP stock. The base fuel differences are however relatively insignificant with respect to distillation and constituency when compared to the change introduced by the ethanol blending" (Orbital Engine Company, 2004).

The investigation presented in the cited report is an extension of earlier tests (Orbital Engine Company, 2003). The aim of the later study, named 2B, included an assessment of durability over accumulated mileage and the following measurements and analyses at specific "breakpoints" (Orbital Engine Company, 2004):

- Exhaust emissions measurements.
- Fuel consumption measurements.
- Engine oil analysis.

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* Australian Energy News (AEN)

- Engine wear analysis at completion of mileage accumulation.
- Fuel system analysis at completion of mileage accumulation.

Since the effects of using ethanol-gasoline blends on engine wear have already been considered in this report discussion here is mainly focused on the emissions. The emission testing included both regulated and non regulated emissions and the main results were as follows. The emission testing included measurements of both regulated and non regulated constituents and the tests were carried out in accordance with the Australian test procedure ADR37/01 for monitoring emissions from light duty vehicles, which includes the US 75 test cycle. The main results were as follows

As can be seen in Table 7.1 there was only a small difference in emission levels when comparing the two fuels at 6 400 km, but the emission performance of E20 was considerably worse than that of the neat gasoline at 80 000 km.

Table 7.1. Regulated emissions at mileages of 6 400 km and 80 000 km.

Regulated Emission (g/km)	Fuel Type				Difference (%)	
	Gasoline		E20			
	6 400 km	80 000 km	6 400 km	80 000 km	6 400 km	80 000 km
THC	0.173	0.097	0.065	0.123	-10.9	26.8
CO	0.710	1.279	0.665	1.881	-6.3	47.1
NOx	0.122	0.177	0.155	0.445	27	151.4

To elucidate the reasons for the observed deterioration in emissions with accumulated mileage associated with use of the blends, the cited authors studied factors that could contribute to their impact on emissions.

Since one of the factors could be the catalyst system, detailed analyses of the individual vehicles were carried out, especially with respect to loss of catalyst efficiency. The catalyst efficiency was studied for each of the three phases of the test cycle, of which Phase 1 (the first 505 sec) is the cold start phase – according to the test procedure the vehicle is initially equilibrated to a room temperature of around 20 to 25 °C. The three phases can be seen in Figure 7.1.

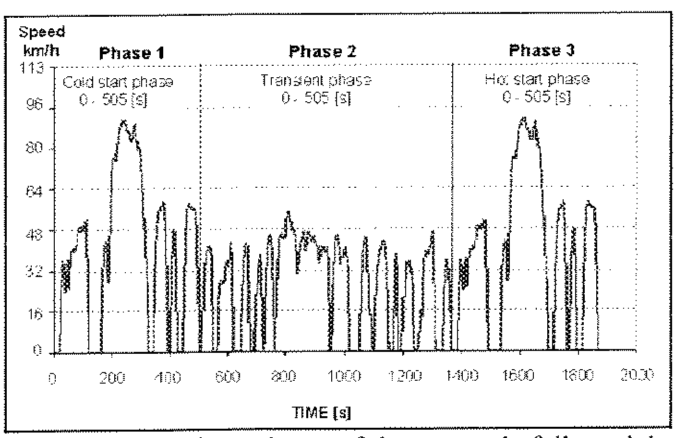

Figure 7.1. The three phases of the test cycle followed during the emission test.

Figures 7.2, 7.3 and 7.4 show the difference in the efficiency of the catalyst found when using the 20 % ethanol blended fuel compared with the use of neat gasoline in each of the three phases.

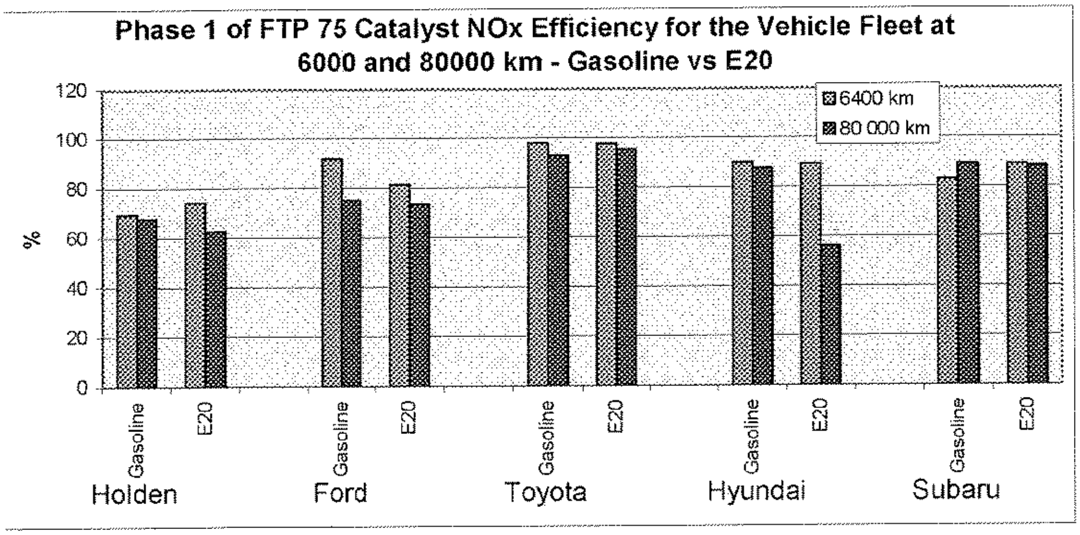

Figure 7.2. Phase 1 NOx catalyst efficiency when using E20 compared with neat gasoline after 6 400 and 80 000km driving

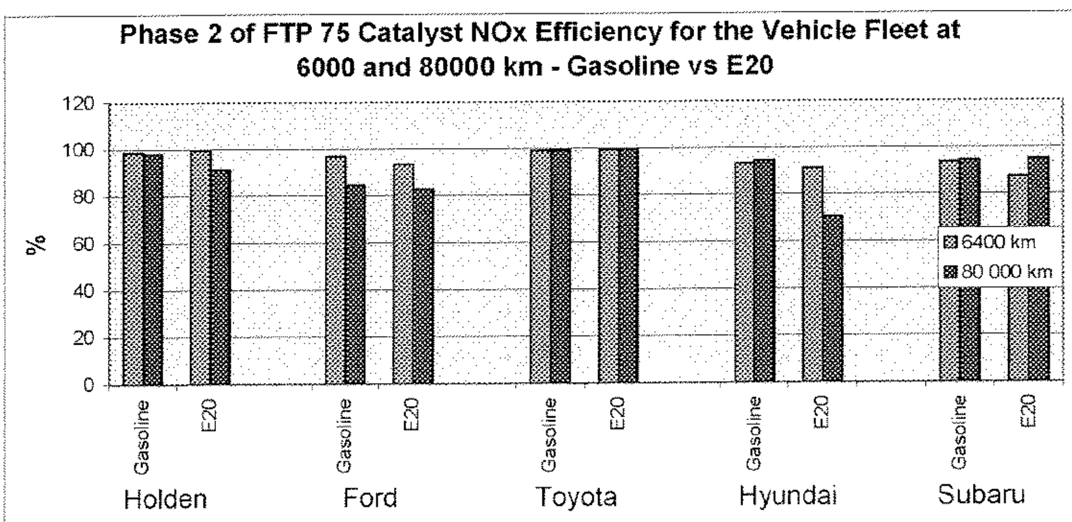

Figure 7.3. Phase 1 NOx catalyst efficiency when using E20 compared with neat gasoline after 6 400 and 80 000km driving.

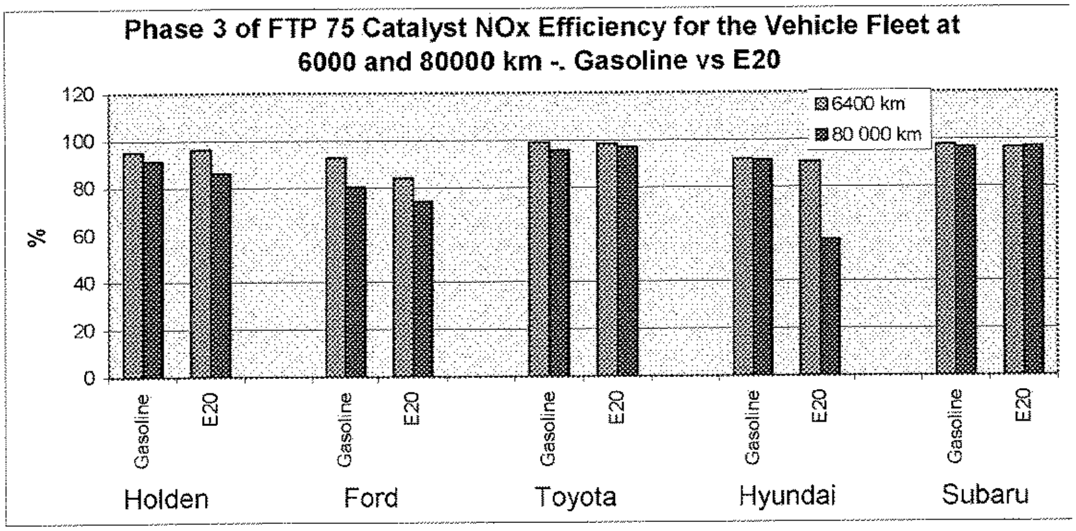

Figure 7.4. Phase 1 NOx catalyst efficiency when using E20 compared with neat gasoline after 6 400 and 80 000km driving.

The three figures show several interesting features:

- There is a considerable difference between the pairs of vehicles. For the Toyota vehicles there is very little difference in catalyst efficiency between use of E20 and use of neat gasoline.
- There is a difference in catalyst efficiency when comparing the three phases of the test cycle. As expected, the efficiency was considerably lower during Phase 1.
- The catalyst efficiency was somewhat higher, at least for some vehicles, during Phase 2 than during Phase 3.
- The most important observation to note is that the deterioration of the catalyst performance was considerably worse when using E20 than when using neat gasoline.

Another factor to consider when studying data from emission tests is the impact of sulphur in the fuel. Studies carried out for the American Lung Association of Minnesota have shown that sulphur in the fuel has a considerable impact on both regulated and unregulated emissions. There is reason to expect the deterioration of the vehicles tested after 80 000 km driving to be linked, to some degree, to sulphur in the fuel used in the tests carried out by Orbital. According to Orbital two grades of gasoline were used in the ethanol blends: unleaded gasoline (ULP) and Perth – unleaded gasoline (PULP). The Australian gasoline specifications at the time of the tests show that the upper limits for the sulphur contents in ULP and PULP were 500 ppm and 150 ppm, respectively. A table taken from the report (Table 7.2) suggests that the ULP grade was used in the neat gasoline tests, but elsewhere it suggests that PULP was also used. Furthermore, it is not clear whether the same grade of gasoline was used for the ethanol-gasoline blends as that used for the neat gasoline tests, although it can be assumed that even a sulphur content of 150 ppm in the base fuel would have had a considerable impact on the emissions.

Table 7.2. Emission data from tests with neat gasoline and 20 % ethanol-gasoline blends.

	Emission g/km	6 400 km		40 000 km		80 000 km		% Difference	
		ULP	E20	ULP	E20	ULP	E20	ULP	E20
Holden	THC	0.120	0.081	0.162	0.155	0.147	0.119	22.5	46.9
	CO	0.711	0.728	0.800	0.865	0.845	0.907	18.8	24.6
	NOx	0.100	0.083	0.106	0.126	0.134	0.208	34.0	150.6
	CO2	256.7	267.6	259.3	265.3	256.8	260.7	0.0	-2.6
Ford*	THC	0.126	0.120	0.112	0.142	0.191	0.218	51.6	81.7
	CO	2.090	1.710	1.871	2.075	4.731	3.798	126.4	122.1
	NOx	0.125	0.265	0.171	0.174	0.457	0.481	265.6	81.5
	CO2	255.7	258.8	255.0	253.5	252.4	250.3	-1.3	-3.3
Toyota	THC	0.025	0.031	0.030	0.024	0.045	0.027	80.0	-12.9
	CO	0.551	0.457	0.873	0.671	1.063	0.895	92.9	95.8
	NOx	0.034	0.036	0.039	0.056	0.070	0.047	105.9	30.5
	CO2	247.5	248.4	235.1	293.8	235.1	236.6	-5.0	-4.7
Hyundai	THC	0.041	0.046	0.049	0.065	0.051	0.112	24.4	143.5
	CO	0.304	0.345	0.472	1.155	0.45	1.821	48.0	427.9
	NOx	0.15	0.18	0.105	0.488	0.132	0.637	-12.0	253.9
	CO2	168.8	172.0	166.4	163.3	166.5	165.8	-1.40	-3.60
Subaru†	THC	0.050	0.041	0.079	0.084	N/A	0.104	58.0	104.9
	CO	0.388	0.288	0.697	0.936	N/A	1.023	79.6	225.0
	NOx	0.059	0.043	0.059	0.048	N/A	0.071	0.0	11.6
	CO2	255.6	254.8	250.0	254.3	N/A	250.6	-2.2	-0.2

7.2. *Evaluation of Emissions in Canada*

A report with a limited‡ distribution from Environment Canada describes a series of comparative tests carried out on five vehicles using neat gasoline and ethanol-gasoline blends (with ethanol contents of 10%, 15% and 20%). The aim of the program was to compare emissions from the vehicles when using neat gasoline and oxygenated fuel (Augin and Graham, 2004). The vehicles used in the tests are listed in Table 7.3 and the fuel properties are shown in Table 7.4.

Table 7.3. Selected data for the tested vehicles.

Vehicle	Model year	Engine displacement [L]	Number of cylinders	Transmission	Test inertia [kg]
Pontiac Grand Am	1999	3.4	V6	Automatic	1590
Honda Insight	2000	1.0	3	Automatic	966
Chevrolet Silverado	1999	5.3	V8	Automatic	2160
Toyota Echo	2001	1.5	4	Automatic	1136
Honda Civic	2001	1.6	4	Automatic	1250

* AENFO02 results are based on tests conducted at 8 900 km rather than 6 400 km.

† AENSU05 results are based on tests conducted at 7 600 km rather than 6 400 km.

‡ In the available edition of the report it is noted that "the report has not undergone detailed technical review by the Environmental Technology Advancement Directorate" Canada.

Table 7.4. Selected data for the fuels used in the emission tests.

Fuel properties	**SGC**[1]	**10 % Ethanol**	**15 % Ethanol**	**20 % Ethanol**
% C by mass	86.7	82.8	81.0	79.3
% H by mass	13.6	13.5	13.5	13.5
% O by mass	-	3.7	5.5	7.3
Density [g/ml]	0.7453	0.7497	0.7519	0.7541

[1]Summer Grade Commercial baseline tests of fuel.

In this section the results from tests of regulated emissions are presented in the form of figures. A more complete set of emission data presented in the report by Augin and Graham is given in the Appendix 1.

The emission tests were carried out in accordance with the US Federal Test Procedure (FTP 75) and two repeats of each cycle were performed on each vehicle in order to provide a minimal measure of the repeatability, according to the authors of the report (Augin and Graham, 2004). The results of the emission tests are shown as means for the five vehicles in Figures 7.5 to 7.9 and Tables 7.5 to 7.7

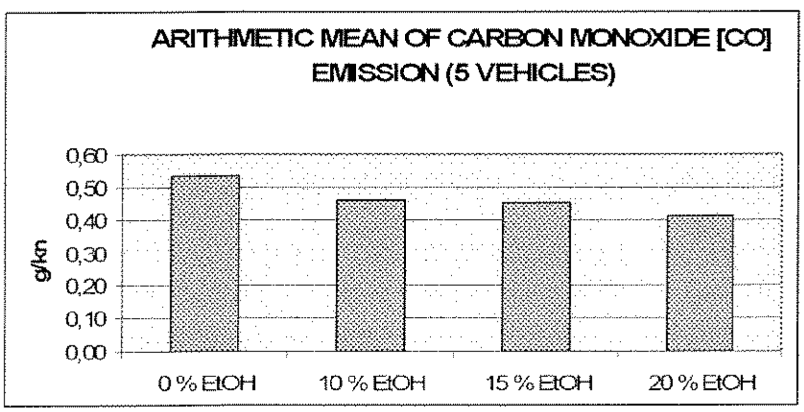

Figure 7.5. Mean emissions of carbon monoxide from the five test vehicles according to the US EPA FTP 75 test procedure

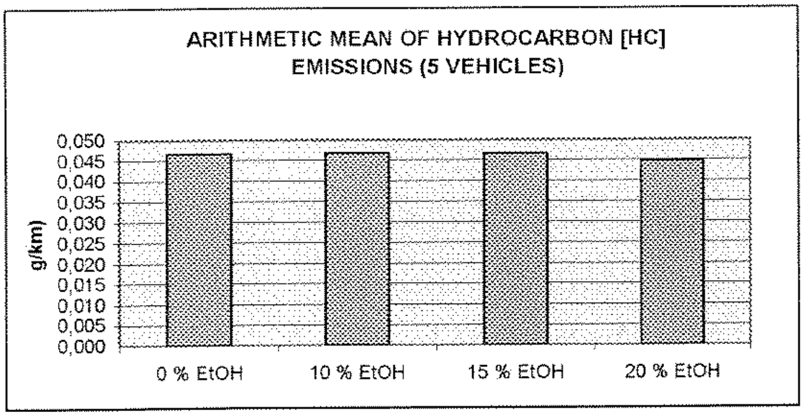

Figure 7.6. Mean emissions of hydrocarbons (HC) from the five test vehicles according to the US EPA FTP 75 test procedure.

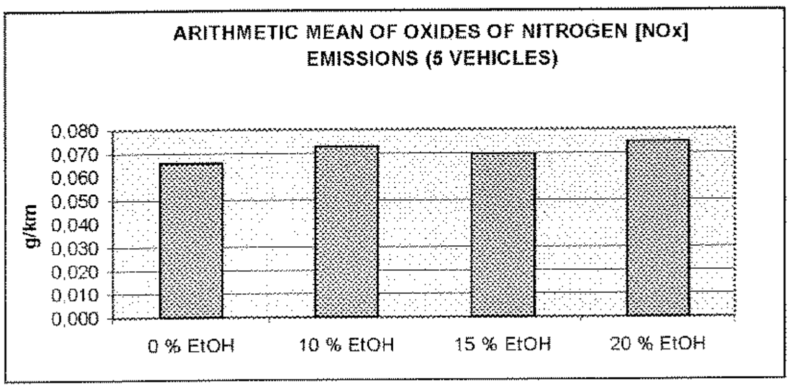

Figure 7.7. Mean emissions of NOx from the five test vehicles according to the US EPA FTP 75 test procedure.

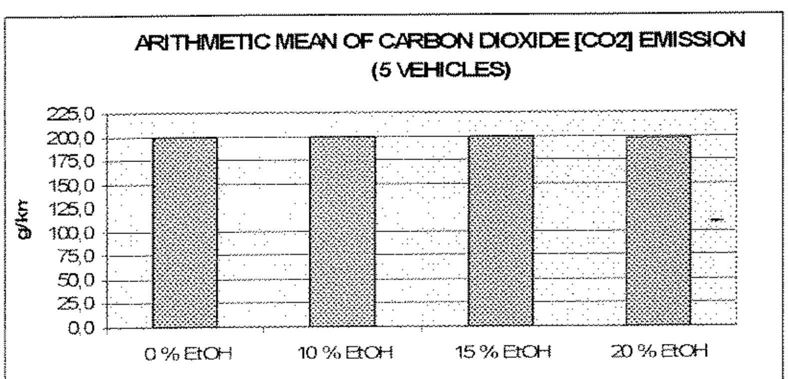

Figure 7.8. Mean emissions of carbon dioxide from the five test vehicles according to the US EPA FTP 75 test procedure.

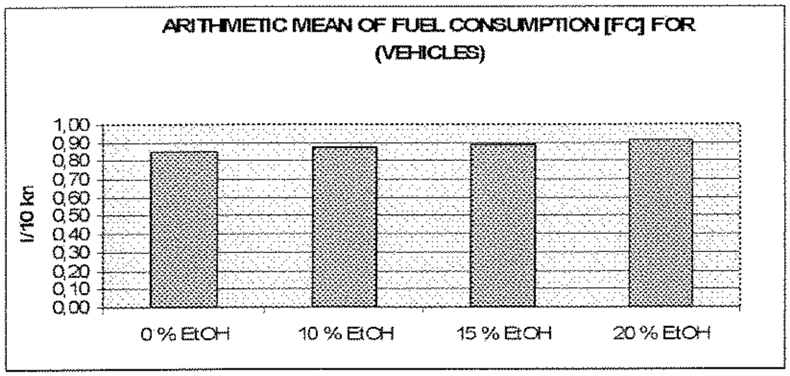

Figure 7.9. Mean fuel consumption of the five vehicles according to the US EPA FTP 75 test procedure.

Table 7.5. Emissions of aldehydes when using neat gasoline and three different blends of ethanol.

	Formaldehyde		**Acetaldehyde**	
Vehicle ⇒	Honda Insight	Grand Am	Honda Insight	Grand Am
US FTP cycle	mg/km	mg/km	mg/km	mg/km
0 % Ethanol	0.019	0.603	0.143	0.298
10 % Ethanol	0.087	0.615	0.273	0.653
15 % Ethanol	0.491	0.516	0.373	0.926
20 % Ethanol	0.665	0.578	0.385	0.814

Table 7.6. Emissions of aldehydes when using neat gasoline and three different blends of ethanol.

	Formaldehyde		**Acetaldehyde**	
Vehicle ⇒	Toyota Echo	Honda Civic	Toyota Echo	Honda Civic
US FTP cycle	mg/km	mg/km	mg/km	mg/km
0 % Ethanol	0.534	0.311	0.261	0.099
10 % Ethanol	0.360	0.870	0.379	0.721
15 % Ethanol	0.690	0.416	1.044	0.435
20 % Ethanol	0.671	0.572	1.311	0.597

Table 7.7. Emissions of specific hydrocarbons when using neat gasoline and three different blends of ethanol.BDL means below the detection limit for the instrument used

	Methane		**Ethylene**		**Acetylene**		**Ethylene**	
Vehicle ⇒	Toyota Echo	Honda Civic	Toyota Echo	Honda Civic	Toyota Echo	Honda Civic	Toyota Echo	Honda Civic
US FTP cycle	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km
0 % Ethanol	4.848	1.952	4.332	2.032	0.615	BDL*	1.311	0.640
10 % Ethanol	4.338	1.417	4.406	1.554	0.622	BDL	1.212	0.261
15 % Ethanol	4.406	1.212	4.344	1.423	0.640	BDL	1.293	0.553
20 % Ethanol	4.829	1.846	4.375	1.541	0.472	BDL	1.181	0.423

* BDL, Below Detection Limit.

The following conclusions can be drawn from the comparisons of the use of ethanol blended fuel and neat gasoline:

- There are considerable variations in the emission levels between different blends of ethanol in gasoline and also between the different vehicles, especially when comparing vehicles with relatively large and relatively small engines.
- As expected, CO emissions decrease when replacing neat gasoline with ethanol blended fuel.
- HC emissions amount to less than 0.1 g/km and there is no clear indication whether blending ethanol in gasoline increases or decreases them.
- For all vehicles except the Toyota Echo NO_x emissions increase when using a blend of ethanol in gasoline. For the Toyota vehicle they decrease.
- According to the presented data it is not clear whether the tailpipe emissions of CO_2 increase or decrease when ethanol is blended with gasoline.
- As expected fuel consumption increases when using a blend of ethanol in gasoline.
- The presented data provide clear indications that the emissions of formaldehyde increase when using ethanol blended gasoline.
- As expected, the acetaldehyde emissions increase when using ethanol blended gasoline. The increase found in this investigation is also quite dramatic compared to corresponding increases found in other investigations discussed in this report.

The emissions of the measured specific hydrocarbons may either decrease or increase when using ethanol blended gasoline.

7.3. Evaluation of Emissions in the UK

A series of emission tests from five vehicles fuelled with a blend of 10% ethanol in gasoline has been carried out by AEA Technology plc*, Harwell, UK, on behalf of the UK Department of Transport. The aim of the tests was to generate data to be used as emission factors for gasoline-fuelled vehicles in the European context. The five vehicles tested are listed in Table 7.8. The Toyota Yaris was tested twice, since significant changes in the test procedure for unregulated emissions was made after the third vehicle was tested (Reading et al., 2002).

Table 7.8. Vehicles selected for emission testing and measurement of fuel economy.

Vehicle identifier	Model	Engine size (litre)	Emission Standards	Mileage km
1 & 6	Toyota Yaris	1.0	Euro III	22 000
2	Vauxhall Omega	2.2	Euro III	19 000
3	Fiat Punto	1.2	Euro II	51 000
4	VW Golf	1.6	Euro III/IV	21 000
5	Rover 416	1.6	Euro II	117 000

The fuels used for the tests were neat gasoline and a blend of 10% ethanol in gasoline. An interesting point to note is that the RVP of the neat gasoline and the blended fuel was 60 kPa 66.5 kPa, respectively.

* AEA Technology is a British technology company.

The emission tests were conducted according to the current European test cycle, ECE/EUDC, and six of the test cycles designed by the Warren Spring Laboratory (WSL), as listed in Table 7.9.

Table 7.9. Test cycles.

Cycle identifie r	Cycle	Hot/cold start	Duration (seconds)	Target distance (km)
1	1 ECE/EUDC (Dir.98/69)	Cold	1180	11.01
2 & 8	WSL Congested	Hot	1030	1.91
3 & 9	WSL Urban	Hot	1205	6.14
4 & 10	WSL Suburban	Hot	480	5.52
5 & 11	WSL Rural	Hot	586	10.95
6 & 12	WSL Motorway 90	Hot	306	7.96
7 & 13	WSL Motorway 113	Hot	256	8.18

The ECE/EUDC tests were carried out following the defined test procedures. The WSL-tests (results from the WSL tests are not presented here) were carried out following the standard procedure for the test laboratory.

It should be noted that only results from ECE/EUDC tests are presented here. In this section the results from tests of regulated emissions are presented in Figures 7.10 to 7.14. A more complete set of emission data presented in the report by Augin and Graham is given in Appendix 1.

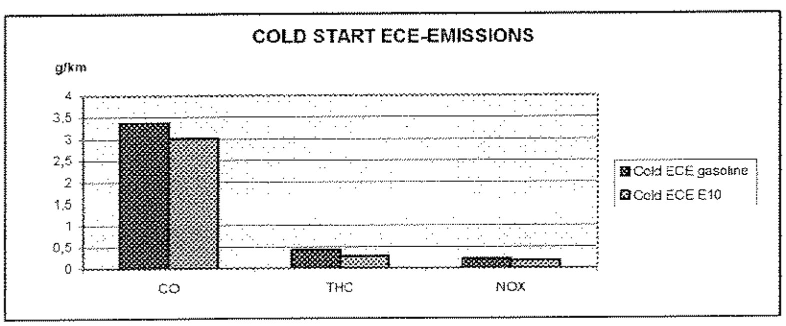

Figure 7.10. Arithmetic mean of five vehicles tested according to the Cold start ECE emission test cycle.

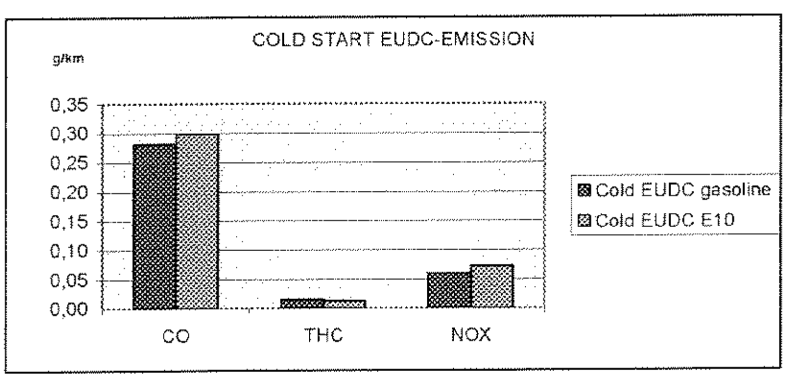

Figure 7.11. Arithmetic mean of emissions from five vehicles tested according to the EUDC Cold start emission test cycle.

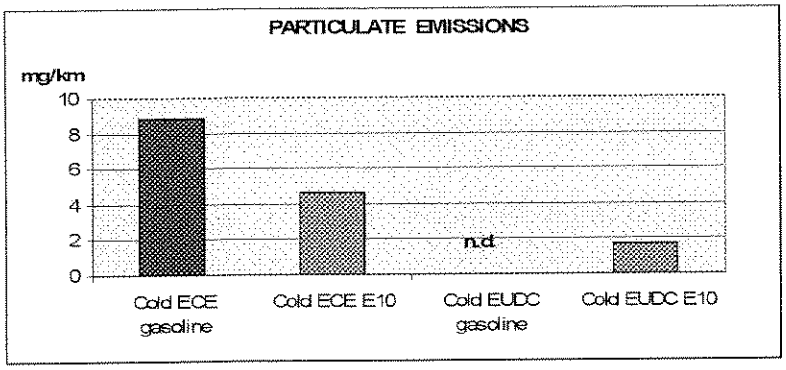

Figure 7.12. Arithmetic mean of particulate emissions in tests according to ECE and EUDC Cold start emission cycles.

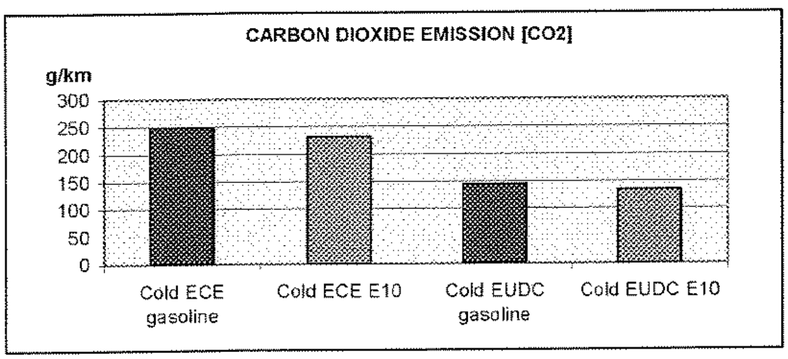

Figure 7.13. Arithmetic mean of CO_2 emissions in tests according to ECE and EUDC Cold start emission cycles.

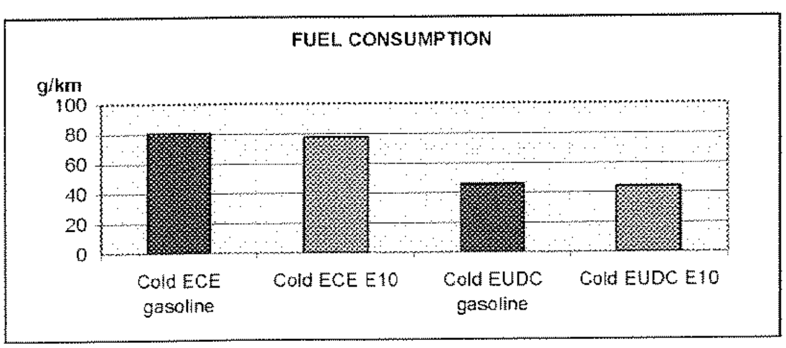

Figure 7.14. Arithmetic mean of fuel consumption in tests according to ECE and EUDC Cold start emission cycles.

When comparing the data from the measurements of fuel consumption and emissions of regulated consitutents, PM and CO obtained using a blend of 10 % ethanol in gasoline with those obtained using neat gasoline the following conclusions can be drawn

- Fuel consumption is slightly increased.
- CO- and PM-emissions are significantly reduced.
- HC emissions are increased rather than decreased.
- NO_x-emissions are not significantly increased.
- For some of the vehicles the tailpipe emissions of CO_2 are decreased.

The unregulated emissions are increased for a few components while the emissions are decreased in most cases. There are significant differences between vehicles, so for some vehicles the emissions are increased while for others they are decreased. As expected, the emission of acetaldehyde is increased in most cases. In the following table the numbers of increases (+) and decreases (-) are presented. Unfortunately, the unregulated emissions were only measured from three vehicles (plus a repeated measurement on the Toyota Yaris) and there are only four comparative measurements for benzene and nitrous oxide. As can be seen in Table 7.10, ammonia and PAH emissions were only measured from three vehicles.

Table. 7.10. Numbers of increases (+) and decreases (-) of unregulated emissions found in the tests using E10 compared to the tests using neat gasoline.

Changes	Methane	1,3-butadiene	Form-aldehyde	Acet-aldehyde	Nitrous oxide	Benzene	Ammonia	ΣPAH
Increase	2	2	2	6	1	1	2	2
Decrease	7	7	7	3	3	3	1	1

7.4. Evaluation of Emissions in Sweden

An extensive investigation was carried out in Sweden in which the amounts of both regulated and non-regulated constituents emitted were compared when using various types of gasoline, LPG, diesel oil, different blends of methanol and a blend with 23 % ethanol in lead-free gasoline (E23) to fuel the following vehicles: five Saabs, five Volvos, one Volkswagen and one Mercedes Benz (Egebäck and Bertilsson, 1983).The tests were carried out on the following vehicles: five Saab, five Volvo, one Volkswagen and one Mercedes Benz. None of these vehicles was equipped with a catalyst. Of all the tests carried out only those involving use of E23 are of interest here. Considering both the amounts of the emissions, and their mutagenicity, the results suggest that use of E23 has both pros and cons. For example, when comparing the use of the 23% ethanol blend in gasoline with the use of neat gasoline, the emissions of ethanol and acetaldehydes increased, while emissions of polycyclic aromatic hydrocarbons (PAHs), especially benzo(a)pyrene (BaP), and NO_x were somewhat lower, as were the mutagenic effects.

Since the temperature in Sweden is rather low in the winter -- occasionally down to minus 20 °C in the Stockholm area and minus 30 °C to minus 40 °C in the north of Sweden – and the mean temperature over the year is around plus 7°C in the Stockholm area (around 0 °C in the north of Sweden), the influence of the outdoor temperature on the emissions generated when using blended fuel and neat gasoline has been studied in a number of projects. It is well known that the use of an alcohol as a fuel in motor vehicles will increase the cold start emissions if the vehicle is not specially designed, i.e. equipped with an engine heater to improve engine starts. In one investigation (Egebäck et al., 1984) five well-maintained and carefully-checked cars without catalytic converters and one equipped with a three-way catalyst system were used. The vehicles were tested with unchanged fuel-air ratio settings (which were set for neat gasoline) with three different fuels. The fuels used were neat gasoline, 5% ethanol mixed with unleaded gasoline (E5), and 15% methanol mixed with a refinery-produced gasoline. All fuels were tested at 22 °C and the neat gasoline and ethanol mixture were also tested at +5° and -7°C.

Since nearly all light duty vehicles with spark ignition engines in Sweden today are equipped with a three-way catalyst the results of the emission testing at different temperatures are of interest for this report. A comparison of the emissions from the catalyst-equipped vehicle adapted for the use of alcohol in neat lead-free gasoline can be seen in Table 7.11.

Table 7.11. Emissions of regulated and non regulated emissions generated when using neat gasoline and E5 at different ambient temperatures. US-73 test cycle.

Fuel	Temp °C	CO g/km	HC g/km	NO_x g/km	Form-aldehyde mg/km	Acro-lein mg/km	Partic-les mg/km	Σ PAH µg/km	B(a)P µg/km	Fuel–cons. l/10km
Gasoline	22	2.27	0.23	0.22	6.6	<0.1	8.2	49	0.9	1.09
	-5	3.90	0.50	0.28	2.3	<0.1	30.1	-	-	1.26
E5	22	2.50	0.36	0.20	6.3	1.2	8.5	33	2.1	1.17
	5	3.10	0.25	0.30	4.2	<1'2	-	-	-	1.24
	-6	2.90	0.43	0.36	1.4	0.6	26.8	71	2.2	1.26

As can be seen from the figures in the above table the ambient temperature has a clear impact on the emissions, especially the particulate emissions and (thus) PAHs. Starting the engine at low temperatures is known to have a stronger effect on the emissions when using fuels with high contents of an alcohol than when using neat gasoline.

Important aspects of adding an alcohol to gasoline to consider are its effect not only on the exhaust emissions, but also on the evaporative emissions and how the fuel is changed by the addition. The aim of an investigation carried out by Laveskog and Egebäck (1999) for the Swedish Transport and Communications Research Board (KFB) was to study the effect of such additions on the RVP of the fuel and the evaporative emissions by adjusting the vapour pressure of the fuel.

Two types of gasoline were ordered from a refinery with vapour pressures (RPV) of 63 kPa and 70 kPa. To elucidate the strength of the effect of adding alcohol on the vapour pressure, samples were sent to a special laboratory for analysis (see "Fuel type", Table 7.12). Both regulated and evaporative emissions were measured (the latter by the standardised SHED method. Ethanol blended fuel was compared with neat gasoline in order to determine how addition of ethanol affects the exhaust emissions and evaporative emissions compared with neat gasoline.

In total, three vehicles were each tested, once, with three test fuels with two different vapour pressures, yielding a total of 18 emission tests. Of the three cars tested, two were equipped with a catalytic converter. The two older cars – a Volvo 240 GL 1985 model and a Volvo 240 DL 1987 model – represented the technology level found in most cars sold in Sweden in the years following 1987 but only the latter had a catalytic converter.. The age of the oxygen sensors and catalysts of this car corresponded to approx. 50,000 km driving in traffic and they were designed to meet the Swedish A12 emission requirements. The other vehicle, equipped with a catalytic converter, was a Saab 9000T and the engine of this car was upgraded to correspond with a 1996 model, equipped with an adaptive fuel supply system, which automatically adjusts the rate of injected fuel according to the energy content of the fuel.

In addition to the emissions tests, the oldest car was also tested for evaporative emissions (SHED test) with the base gasoline (71.5 RVP), base gasoline (64 RVP) + 10% ethanol, and base gasoline (71.5 RVP) + 25% ethanol. The emission test results and the fuel consumption for the catalyst-equipped cars (Volvo DL and Saab 9000T) are presented in Tables 7.13 and 7.14.

Table 7.12. Analysed and calculated values for test fuels.

Fuel type	Density	Ethanol	Energy content	RVP, kPa
	g/mL	%	MJ/kg / MJ/l	analysed
Gasoline with lower vapour pressure (63 kPa)				
Unmixed gasoline	0.750	<0.5	43.9 / 32.9	64
10% ethanol with gasoline	0.754 [1)]	10	42.2 / 31.8 [2)]	69
25% ethanol with gasoline	0.760 [1)]	25	39.7 / 30.2 [2)]	67
Gasoline with higher vapour pressure (70kPa)				
Unmixed gasoline	0.755	<0.5	43.8 / 33.1	71.5
10% ethanol with gasoline	0.759 [1)]	10	42.1 / 32.0 [2)]	76
25% ethanol with gasoline	0.764 [1)]	25	39.6 / 30.3 [2)]	73

[1)] The density of ethanol is 0.791 g/mL at 18 °C according to

[2)] The energy content for ethanol is set to 27.1 MJ/kg

Table 7.13. Results of measurements of exhaust emissions during an urban driving cycle (UDC) according to US standards. Volvo 240 GL, 1985 model. Base gasoline, 64 kPa and 71.5 kPa.

Car	Amount EtOH%	Exhaust System	RVP kPa	CO g/km	HC g/km	NO_X g/km	CO_2 g/km	NMHC g/km	Fuel consumption l/10 km
Volvo DL	0% EtOH	Cat.	64	2.15	0.21	0.17	243	0.18	1.00
	10% EtOH	Cat.	69	1.82	0.17	0.18	240	0.15	1.03
	25% EtOH	Cat.	67	1.13	0.12	0.23	235	0.10	1.06
	0% EtOH	Cat.	71.5	2.11	0.17	0.19	243	0.14	1.01
	10% EtOH	Cat.	76	1.71	0.15	0.17	240	0.13	1.04
	25% EtOH	Cat.	73	0.98	0.13	0.30	238	0.11	1.08

Table 7.14. Results of the measurement of exhaust emissions during an urban driving cycle (UDC) according to US standards. Saab 9000 CS, 1996 engine and engine management system. Base gasoline 64 and 71.5 kPa.

Car	Amount EtOH%	Exhaust System	RVP kPa	CO g/km	HC g/km	NO_X g/km	CO_2 g/km	NMHC g/km	Fuel consumption l/10 km
Saab 9000 T	0% EtOH	Cat.	64	1.16	0.06	0.14	242	0.05	0.99
	10% EtOH	Cat.	69	1.06	0.06	0.14	253	0.05	1.08
	25% EtOH	Cat.	67	1.23	0.05	0.13	250	0.04	1.13
	0% EtOH	Cat.	71.5	1.13	0.06	0.16	251	0.05	1.03
	10% EtOH	Cat.	76	1.09	0.06	0.15	244	0.05	1.04
	25% EtOH	Cat.	73	1.25	0.07	0.12	238	0.06	1.08

The CO and HC emissions were lower for the Volvo with a catalytic converter (Table 7.13). NO_X emissions increased significantly when the gasoline with a vapour pressure of 64 kPa was used, but insignificantly with the 10% mixture. Despite the increase, the NO_x emissions were still lower than the emission standards for this car. When gasoline with a vapour pressure of 71.5 kPa was used, all emissions decreased slightly with the 10% ethanol mix. With the 25% ethanol mix, NO_X emissions rose from 0.19 g/km to 0.30 g/km. Efficiency also seemed to increase for this car, as the increase in fuel consumption for ethanol mixtures does not correspond to the reduced energy content of the test fuel.

In the car with an adaptive fuel supply system the effect of the ethanol mixture on CO emissions appears to be small, and the already very low level of HC emissions were almost totally unaffected (Table 7.14). NO_X emissions were low, and showed a tendency to fall further as the ethanol content in the fuel increased. In the tests with the fuel with an RVP of 71.5 kPa, the tendency was the same as for the other cars -- the fuel consumption was lower than expected when ethanol was added to the gasoline. The comparison of these two cars indicates that a car with an adaptive emission control system has better emission characteristics than a car without such a system.

Unfortunately, evaporative emission tests were only carried out on the Volvo 240 GL, 1985 model, which lacked a catalyst and canister for trapping fuel vapour. The results from the tests of this car are presented in Table 7.15.

Table 7.15. Evaporative losses from a car without evaporation controls, Volvo 240 DL, values from single measurements using fuels with 0% and 10% ethanol contents.

HC emission	**g/test**	**Increase in emissions [%]**
Base gasoline, 71.5 RVP	37.2	-
Base gasoline, 64 RVP +10% ethanol	38.9	4.6
Base gasoline, 71.5 RVP +10% ethanol	42.4	14

7.5. *Evaluation of Emissions in the USA*

Few American studies were found in the literature survey that included measurements of emissions from commercial gasoline-based fuels with low alcohol contents suggesting that such measurements and studies have low priority in the USA, including California. However, it should be borne in mind that gasoline blended with 10% ethanol has been commonly used in many areas in the USA during the last 20 to 25 years. In contrast to the few reports found for blends with low ethanol contents a number of studies were found concerning emissions from FFVs.

In Minnesota a series of studies, initiated by the American Lung Association of Minnesota on the exhaust emissions from gasoline with low alcohol contents was found. The emission measurements were carried out at the University of North Dakota and the U.S. Department of Agriculture part-funded the work. In Minnesota a series of studies was commissioned by the American Lung Association of Minnesota on the exhaust emissions from gasoline with low alcohol contents (Aulich and Allen, 2002). The emission measurements were carried out at the University of North Dakota and the U.S. Department of Agriculture part-funded the work.

Since 1999, the American Lung Association of Minnesota has been presenting studies on the impact on emissions of sulphur in the fuel and this issue has been discussed in a number of reports, which have shown that the emission rate depends considerably on the fuel used. The aim of the investigation discussed here was to further study the impact on emissions of the sulphur, benzene and olefins contents in gasoline. Minnesota gasoline is regulated under the Antidumping* Requirements introduced by the EPA and therefore it is of interest to study whether these requirements are fulfilled. The Antidumping Statutory Baseline Fuel Parameters set by the US EPA are shown in Table 7.16.

Table 7.16. EPA Statutory Antidumping Baseline Fuel Parameters.

	Summer	Winter	Average Annual
Benzene, vol%	1.53	1.64	1.60
Aromatics, vol%	32.0	26.4	28.6
Olefins, vol%	9.2	11.9	10.8
RVP, psi	8.7	8.7	8.7
E200, vol%	41.0	50.0	46.0
E300, vol%	83.0	83.0	83.0
Sulphur, ppm	339	338	339

In 1999 the EPA introduced more rigorous emission standards, necessitating amendments to the fuel requirements. Since the sulphur content is one of the most important variables to reduce in the fuel, the EPA has established new requirements for the sulphur content in gasoline. According to the Federal Register / Vol. 65, No. 28 / Thursday, February 10, 2000 / Rules and Regulations the level of sulphur should be reduced, on average, to 15-40 ppm by weight and limited to a maximum of 80 ppm by 2006, see Table 7.17.

Table 7.17. Gasoline sulphur requirements according to the Federal Register, February 10, 2000.

	Gasoline sulphur standards for the averaging period beginning:		
	January 1, 2004	January 1, 2005	January 1, 2006 and subsequent
Refinery or Importer Average	N/A	30.00	30.00
Corporate Pool Average	120.00	90.00	N/A
Per-Gallon Cap	300	300	300

The paper by Aulich and Allen of the Environmental Research Center, University of North Dakota, released by the American Lung Association of Minnesota, reports results from an evaluation of the impact of fuel sulphur on emissions. Samples of gasoline from three different gasoline suppliers were analyzed in detail and the impact of the fuel sulphur content was evaluated by using the resulting fuel data as inputs in the EPA's MOBILE6.2 vehicle emission

* The purpose of the Antidumping Requirements is to ensure that conventional gasoline is not more polluting than it was in 1990. See Federal Register / Vol. 65, No. 230 / Wednesday, November 29, 2000 / Rules and Regulations.

modelling software (US EPA 1993). In all, 23 samples of fuel containing 9.2 to 9.8 % ethanol were analyzed. The results of this part of the evaluation are summarized in Table 7.18.

Table 7.18. The estimated impact of fuel sulphur content on HC and NO_x emissions. Holiday, Amoco and SA (SuperAmerica) are gasoline companies.

	Holiday	**Amoco**	**SA**
HC, g/km	0.069	0.095	0.098
NOx, g/km	0.31	0.50	0.51
Sulphur in Fuel, ppm	57	167	188

Two other components in the fuel that have a significant impact on the emissions are olefins and benzene. Benzene, a single component of gasoline, is known to have an effect on people's health while olefins comprise a group of hydrocarbons that are known to be reactive in the atmosphere and may also cause deposits in the fuel system of the vehicle. Therefore, there is a need to keep the contents of these components as low as possible in gasoline.

The results of the evaluation conducted by Aulich and Allen on the impact of olefins and benzene in the fuel are summarized in Table 7.19.

Table 7.19. The estimated impact of the fuel contents of olefins and benzene on emissions of 1,3 butadiene and benzene. Holiday, Amoco and SA (SuperAmerica) are gasoline companies.

	Holiday	**Amoco**	**SA**
1.3 **Butadiene**, g/km	0.00034	0.00071	0.00050
Benzene, g/km	0.0035	0.0064	0.0055
Olefins in Fuel, %	6	17	7
Benzene in Fuel, %	0.9	2.3	1.4

In another study presented by the American Lung Association of Minnesota (2003) the five blends of fuel listed in Table 7.20 were studied to assess the impact of sulphur.

Table 7.20. Average Fuel Properties (American Lung Association of Minnesota, 2003).

	Holiday E10	**BP E10**	**SA E10**	**Non-ethanol**	**E85**
Ethanol, vol%	10.2	10.2	10.3	0.0	78.4
Aromatics, vol%	23.6	24.2	24.3	30.5	N/A
Olefins, vol%	8.5	15.5	7.7	9.1	N/A
Benzene, vol%	1.0	1.9	1.1	N/A	N/A
Sulphur, ppm	49	212	90	103	8

The emission tests followed the "hot start" phase of the FTP-75 test cycle. The results of the tests carried out on a dynamometer and the data evaluation for the fuels listed in Table 7.19 are shown in Table 7.21.

Table 7.21. The impact of fuel sulphur content on HC and NO_x emissions.

	Holiday	**BP**	**SA**	**Non-ethanol**	**E85**
HC, g/km	0.005	0.097	0.072	0.056	0.010
NOx, g/km	0.019	0.080	0.108	0.119	0.037
Sulphur, ppm	49	212	90	103	8

The cited study emphasises that:

- HC and NO_x emissions for the Holiday fuel were under the detection limits, and the estimated levels of these emissions had to be based on their respective detection limits.
- For the BP fuel HC emissions were consistent with the predictions according to MOBILE6.2, but the levels were higher than for the other fuels tested.
- For the non-ethanol fuel with a sulphur content of 103 ppm, HC and NO_x emissions were similar to those for the BP and SA fuels.
- The emissions of HC and NO_x were much lower for E85, which had a sulphur content of just 8 ppm, than for the other fuels.

The measured emissions were significantly lower than the levels predicted by the EPA model, possibly because the tests were carried out with hot cycles while the EPA predictions were based on a complete, cold start FTP cycle.

7.6. *Fuel Consumption*

The consumption of fuel is either measured and presented as fuel consumption (L/10 km or L/100 km), or as fuel economy (miles/US gallons) in the USA and Canada. Adding an alcohol such as ethanol to gasoline at up to 5 to 10% may result in a minor increase in the volumetric fuel consumption. In a paper from the Canadian Renewable Fuels Association it is declared that although a 10 % ethanol blend contains about 3 % less energy than neat gasoline, the difference in energy content "is compensated by the fact that the combustion efficiency of the ethanol-blended fuel is increased" (Canadian Renewable Fuels Association, 2004).

This statement is consistent with findings by Laveskog and Egebäck, since their investigation (discussed in section 7.4) indicated that the lower energy content of the blended fuel was to a certain degree compensated by its higher combustion efficiency (Laveskog and Egebäck, 1999).

However, according to some other sources, e.g. a literature review prepared by the Orbital Engine Company for Environment Australia, there is a direct proportionality between fuel economy and the energy content of the ethanol-gasoline blend (Orbital Engine Company, 2002). In another report Orbital Engine Company has presented results from measurements of fuel consumption according to the Highway Fuel Economy Cycle (HWFET), as shown in Figure 7.15 (Orbital Engine Company 2004).

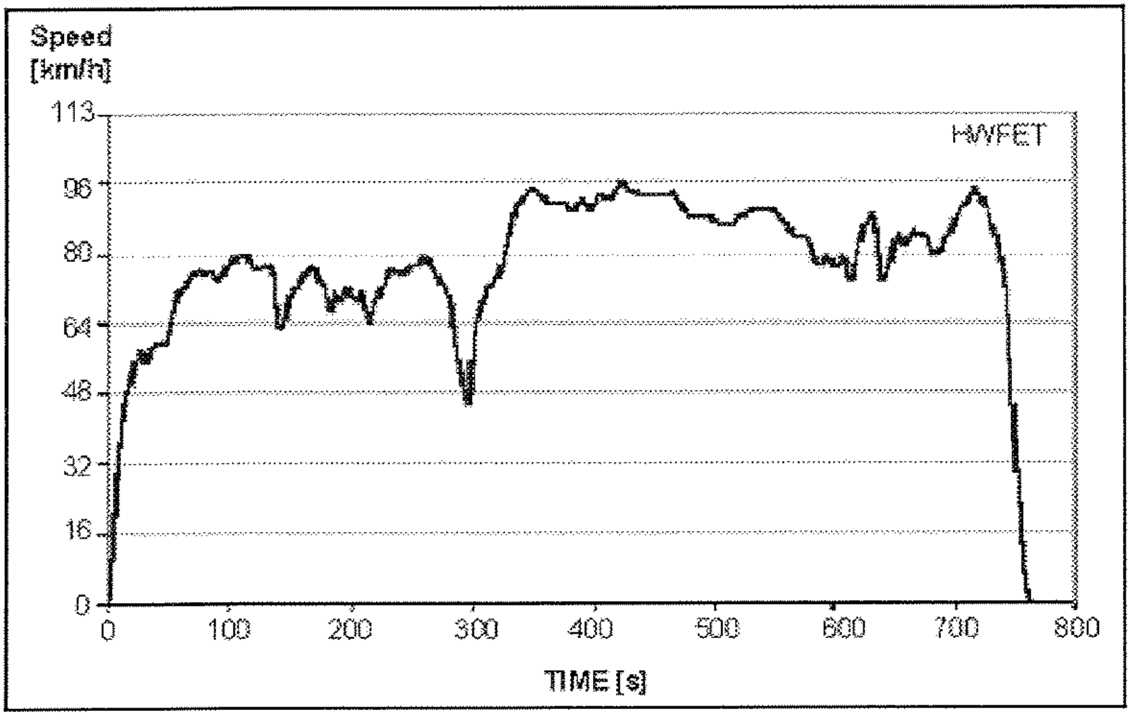

Figure 7.15. The EPA Highway Fuel Economy Cycle.

The measurements of emission and fuel consumption were carried out on five vehicles of "newer" models and comprised tests in which both gasoline and ethanol were used in the same vehicle in order to generate comparative data. Some results of the emission measurements carried out by the Orbital Engine Company to study the efficiency of catalysts are presented in section 7.1, and in the following figures (7.16-7.18) the fuel consumption results are presented.

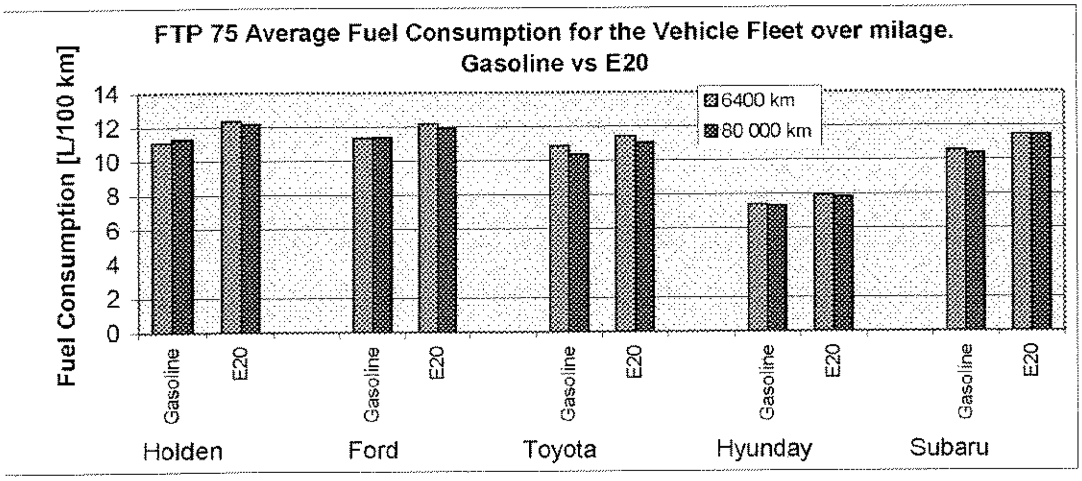

Figure 7.16. Average fuel consumption of the tested vehicles at 6,400 and 80 000 km when driving according to the cycle city

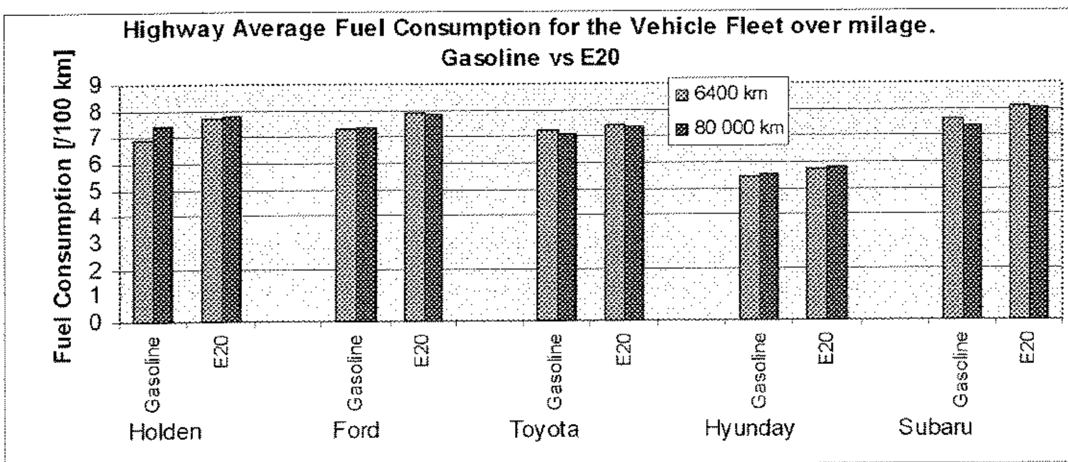

Figure 7.17. Fuel consumption of the tested vehicles at 6,400 and 80 000 km when driving according to the city cycle

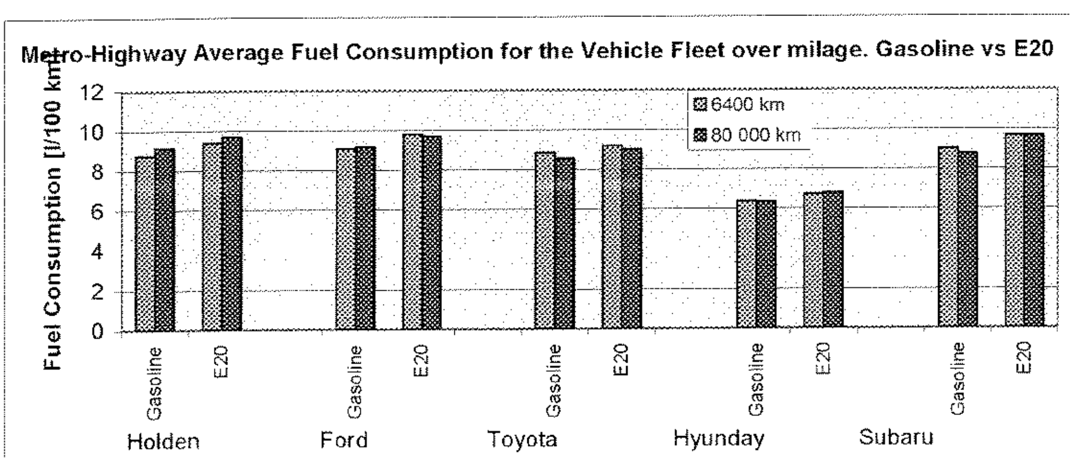

Figure 7.18. Average fuel consumption of the tested vehicles at 6,400 and 80 000 km when driving according to the city cycle.

A research project has been carried out on 15 vehicles of models from different years by a group at the Minnesota Centre for Automotive Research, Minnesota State University. Two blends of ethanol in gasoline, E10 and E30, were used during the test program, which was carried out to measure fuel consumption and emissions, and to analyse drivability characteristics, engine wear and material compatibility. The vehicles were tested on a chassis dynamometer according to both the hot 505 section of the standard test cycle and on the road when driven by owners of the cars. The fuel consumption and energy used per unit distance in the chassis dynamometer tests were matched to the distance driven in the on-road tests, based on the volumetric consumption. Oil samples were taken to analyse particles in the oil to evaluate whether accelerated wear of the engine had occurred. During the on-road tests the vehicles were driven by their owners (Bonnema et al., 2004).

The drivers were asked to fill in forms, the first of which concerned fuel consumption, while a second concerned maintenance, including changes to the car, such as changes of tyres or other parts which could have affected the results of the study. A third form concerned drivability. Consequently, the drivers of the cars during the field tests had to collect samples of oil for analysis and to record data concerning:

- maintenance and performance of the vehicles.
- fuel consumption.
- drivability complaints.

The results for fuel economy obtained in the Hot tests on the chassis dynamometer are summarized in Table 7.22.

Table 7.22. Fuel consumption and energy use when tested according to Hot 505 procedures (Bonnema et al., 2004).

Vehicle	**E10 l/10 km**	**E30 l/10 km**	**% Diff,**	**E10 MJ/10 km**	**E30 MJ/10 km**	**% Diff.**
1996 Oldsmobile Acieva	1.01	1.19	+14.66	31.93	34.52	+8.11
1998 Dodge Caravan	1.09	1.24	+12.24	34.22	35.98	+5.16
1997 Chevrolet K3500	1.85	1.97	+6.14	58.33	57.37	-1.66
1994 Buick Regal	1.06	1.09	+2.96	33.28	31.64	-4.92
1997 Chevrolet K 1500	1.69	1.86	+8.99	53.26	54.01	+1.41
1998 Ford F-250	1.84	2.01	+8.74	57.81	58.42	+1.06
1997 Ford Taurus	1.28	1.29	+1.30	40.23	37.60	-6.54
1997 Ford F-150	1.65	1.85	+0.78	51.90	53.65	+3.38
1990 Chevrolet C1500	1.09	1.22	+10.42	34.46	35.50	+3.00
1992 Chevrolet K1500	1.51	1.68	+9.88	47.56	48.70	+2.39
1992 Geo Metro	0.62	0.69	+11.04	19.42	20.15	+3.73

\+ indicates an increase in fuel consumption or energy use when comparing E30 with E10.
\- indicates a reduction in fuel consumption and energy use when comparing E30 with E10.

It should be noted that the authors of the present report have not had access to appendices to the cited report, and hence have not been able to verify the interpretation of the data collected.

However, the data in the above table indicate that there were differences between vehicles with respect to the effects of the ethanol blend in gasoline. Fuel consumption increased on a volumetric basis when E30 was used instead of E10, as expected, and the differences varied from less than 1% to over 12 %, which was less than expected. Concerning the energy used, the influence of using ethanol-gasoline blends with higher ethanol contents should be similar to their effect on fuel consumption, but as can be seen, the table shows a decrease for three of the vehicles. This may be due either to these vehicles being more energy efficient, or to uncertainties in the measurement of fuel consumption.

The fact that vehicle studies have found a great diversity of responses to increasing ethanol content in terms of fuel consumption can be explained in a number of ways. However, a complicating factor is that the cited studies do not supply specific information on either the engine specifications or the fuels used for testing, although knowledge of these variables is essential for fully understanding the data.

For example:

If a test compares a fuel with no ethanol and one with a 10% ethanol content, and it is run in an area where the base fuel used has a relatively low octane number, the lower energy content of the ethanol blend may be somewhat compensated by its higher octane rating, provided that the engines used have advanced ignition (knock control) systems according to Chandra Prakash (1988).

Carburetted vehicles may be affected by lean-mix problems if adjusted to a "low fuel consumption" setting, especially during acceleration and take-off from standstill.